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DESIGN AND EVALUATION OF A PREDICTOR FOR REMOTE CONTROL SYSTEMS OPERATING WITH SIGNAL TRANSMISSION DELAYS

by John E. Arnold and Paul W. Braisted

Prepared under Grant No. NsG-111-61 *by*
STANFORD UNIVERSITY
Stanford, California
for

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SUMMARY

An experimental program is conducted to investigate the ability of a predictor to aid a human operator in the remote control of a vehicle operating with a signal transmission lag.

A series of tracking experiments is conducted with an experimental vehicle. An upper bound of tracking performance is established by driving without a signal transmission lag. A lower bound is established by driving with a signal transmission lag. The ability to drive with the predictor can be seen in relation to these upper and lower bounds. The results of the tracking experiments show that the predictor makes it possible to drive nearly as well with a signal transmission lag as to drive at the same speed without a signal transmission lag.

In order to free the driver from having to follow a prepared line or track, a maze is used that involves open areas with a series of limited objectives in the form of gates, or wickets. The ability of the predictor to aid the human operator is determined. The results of the maze experiments show that the predictor is not needed in open areas where no precise control is required. The predictor is needed in approaching and driving through congested areas. Subjective reactions of the experiments are noted.

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CHAPTER I

INTRODUCTION

A. PROBLEM STATEMENT

The problem discussed in this paper has to do with the effects of signal transmission lag on the human control of robot vehicles using video feedback. The task is to investigate ways for negating the adverse effects of signal transmission lags on the human operator so that significantly greater speeds can be maintained than is possible without this effort.

B. OBJECTIVES

The objectives of this work were to develop and to evaluate a device that will make it possible to avoid the detrimental effects of signal transmission lag.

The device that was developed is called a predictor. As a predictor it anticipates the future behavior of the robot vehicle responding to the steering commands that were sent by the human operator. This anticipatory information is presented to the human operator in the form of a marker superimposed on the television picture received from the vehicle. The television picture from the robot vehicle shows the landscape over which the vehicle will travel. The marker responds immediately to all commands. It carries out immediately all maneuvers that the television picture will show the vehicle carrying out some time later. By driving the marker, the human operator imagines that he is driving without a signal transmission lag, because there is no delay between the time at which he issues a command and when he sees the response of the marker.(Fig. 1).

There are three goals in the experimental evaluation of the predictor system. First, numerical data is desired to measure the success of the predictor in helping the human operator recover the control that is lost when the signal transmission lag is introduced into the system. Second, subjective results should be obtained. These will be important in helping future designers of predictor systems, and they will contribute to our understanding of human behavior when predictors are used. Third, there is an expectation that the experience gained in using the predictor system will reveal areas of particular importance for future studies.

In collecting numerical data, it is important to consider the way in which these data can be obtained. The human operator is confronted with a tracking problem. He observes a landscape appearing on the television display and tries to steer the robot vehicle so that it will follow or track a particular route over the terrain.

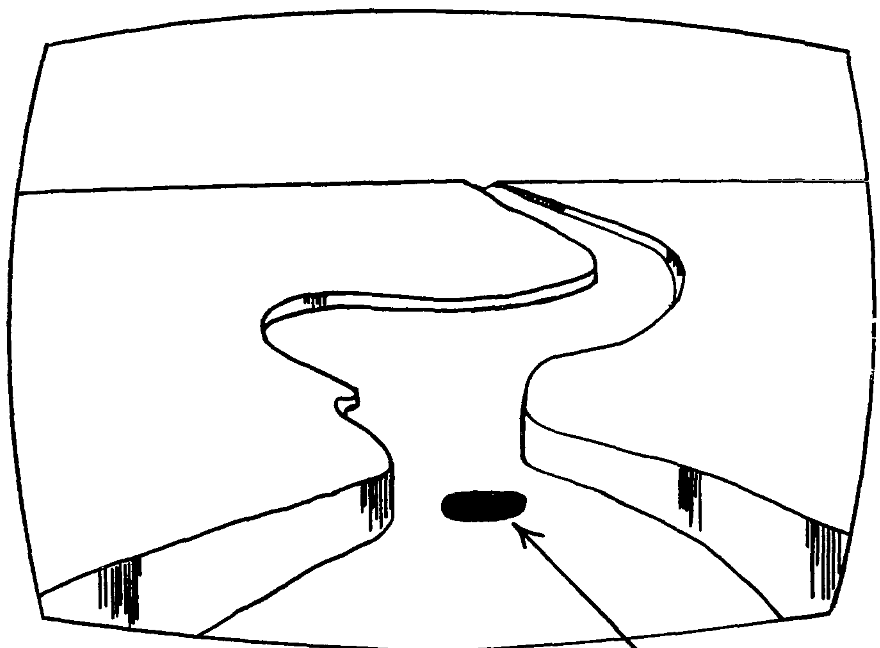


FIG. 1 PREDICTOR MARKER SUPERIMPOSED
ON VIDEO PICTURE OF LANDSCAPE

An upper bound of tracking ability can be established by measuring the skill with which tracking can be done when there is no signal transmission lag. A lower bound can be established by observing the difficulty in tracking when there is a signal transmission lag and no predictor. The ability to drive with the predictor can then be seen in relationship to these upper and lower bounds. The upper bound serves as a goal of achievement that is sought by the predictor, while the lower bound indicates the seriousness of the problem that is to be improved.

In this study we are concentrating on the way in which a predictor can help the human operator when a signal transmission lag is present. The predictor is intended as an aid when there are various amounts of signal transmission lag. Since the remote control of a lunar vehicle from the earth is the most immediate possible application of this technique, the lunar situation with its 2.6 seconds total signal transmission lag is used in this paper for illustrative purposes.

This project is part of a continuing work at Stanford University sponsored by the National Aeronautics and Space Administration. In the first stages of this program, Adams (1,2)* studied the effects of signal transmission lag without a predictor. The present work continues by developing and evaluating a predictor system to aid the human operator. A consideration of weight, reliability, and power demands led to the governing policy of placing only a television camera on the robot vehicle and of keeping the system complexities at the control station. As far as is known, the present development is the first operational predictor system for use where there are long signal transmission lags.

As vehicle speeds and the length of the signal transmission lag are increased in future phases of this work, the capabilities of the present approach will be exceeded. When that stage is reached, it will be necessary to add equipment to the robot vehicle that will enable the vehicle to maneuver with only periodically received programs of instructions. The vehicle will need the ability to improvise to some extent and to take evasive action to avoid obstacles. Above all, the vehicle will need the ability to stop and wait for further instructions when it is faced with an unexpected problem that it can not handle.

Although the Prospector mission for which this present work was originally intended may be passed over in favor of going directly to the Apollo manned, lunar mission, the knowledge that will be gained in this study will be useful for other remote control situations that will

*Numbers refer to publications listed in the references.

undoubtedly be encountered in the future.

C. SYSTEM DELAYS

Throughout this paper the term system delay will be used to cover all the effects that prevent the human operator from being able to observe immediately the full consequences of his input commands. Delays may occur in both the feed forward and the feedback loops in a control system, but here our interest is in the total delay that occurs between the time the human operator issues a command and the time he receives feedback describing the way in which the vehicle carries out the command.

Within this definition of system delay, a signal transmission lag is only one of the ways in which delays are introduced into a system. An important source of system delay in many cases is due to the slow dynamic response of the machine being controlled. The term dynamic lag is used in this paper to cover all situations where system delays are caused by the dynamic response of the controlled vehicle. Another source of system delay is the result of human reaction time. This is the time required for the human being to react to each stimulus he receives.

Fig. 2 shows the places where signal transmission lag and dynamic lag may appear in a feedback system. For simplicity in the illustration, the human reaction time is ignored and the human operator is treated as the summing element in the system where he combines the effects of input and feedback signals.

As related to our problem of the control of a robot vehicle, a signal transmission lag is shown in the feed forward loop representing the time required for radio signals to travel through space from the earth-bound control station to the vehicle. A block is shown to indicate that the robot vehicle may require time to respond to each command. The time constitutes the dynamic lag in the system. The output is a change of the direction in which the vehicle is travelling over the ground. A television camera is carried on the vehicle and observes the direction of travel and the landscape that the vehicle will traverse. The video picture is fed back to the human operator. A signal transmission lag is shown for the feedback transmission.

In the experimental arrangement developed for the present study (Fig. 3), several modifications of system delays are made. The first point is to emphasize that this project is concerned with the effects of signal transmission lag only, and is not concerned with dynamic lags. Consequently, a highly-responsive and maneuverable vehicle was built for test purposes. It will be shown in detail later that the test vehicle steers by changing the direction of travel in direct relationship to the angular displace-

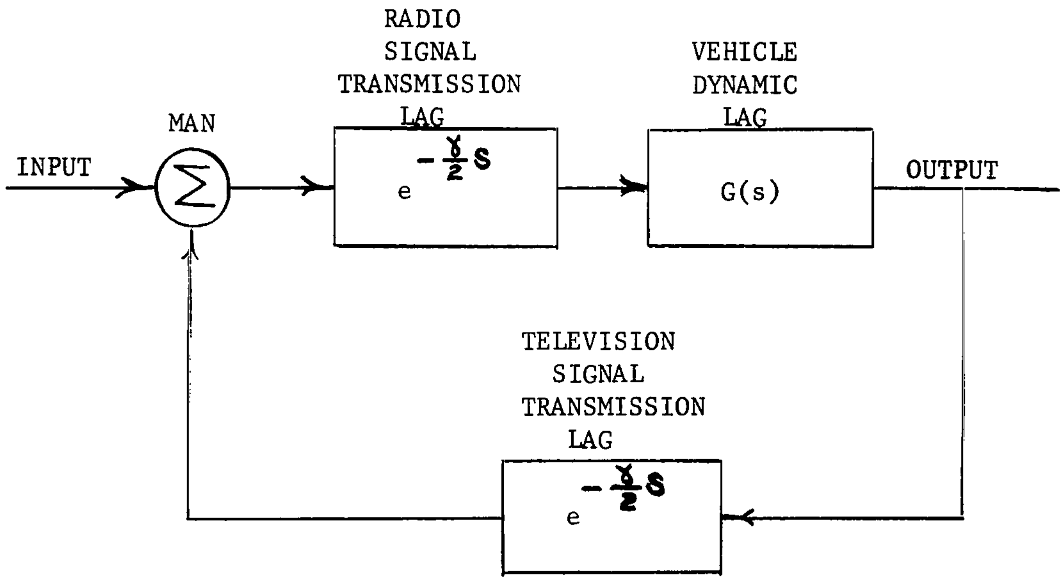


Fig. 2 SIGNAL TRANSMISSION AND DYNAMIC LAGS IN FEEDBACK CONTROL SYSTEM

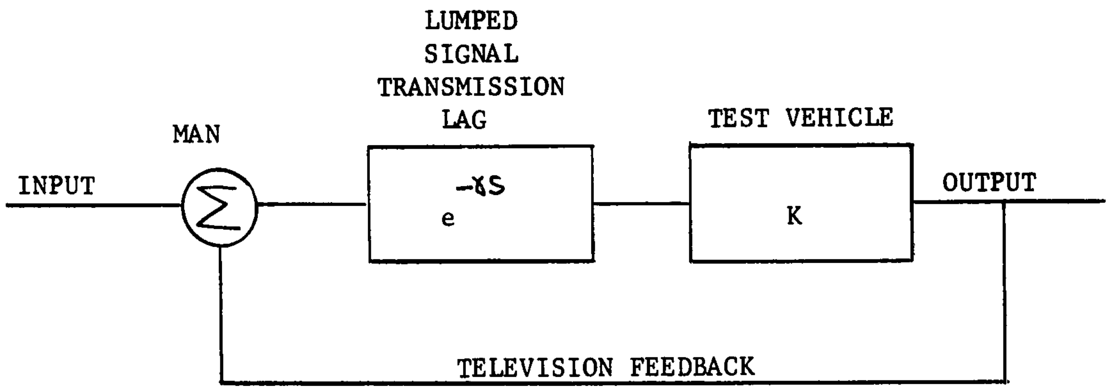


Fig. 3 LUMPED SIGNAL TRANSMISSION LAG IN EXPERIMENTAL STUDY

ment of the steering wheel used by the human operator in the control station. The vehicle follows these changes in direction with a negligible dynamic lag. The primary source of delay is due to signal transmission lag. The vehicle behaves essentially like an amplifier with its direction of travel directly related to the angular position of the operator's steering wheel.

Fig. 3 also shows that the signal transmission lag is lumped in the feed forward loop for the experimental setup. By lumping the entire signal transmission lag in the radio link from the control station to the robot vehicle, the problem of delaying video signals are avoided. This lumping is justified in the discussion of the experimental arrangement. Fig. 3 shows the location of the system delay in the experimental simulation of a real mission where the system delay may be distributed as shown in Fig. 2.

D. BACKGROUND STUDIES MADE ON THE EFFECTS OF SYSTEM DELAYS

A number of experimenters have considered the effects on human behavior caused by dynamic lag in a man-machine control system. These studies have been carried out in laboratory simulation of situations that occur with slowly responding machinery. Notable is the work of Conklin (3). Conklin considered dynamic lags of up to 16 seconds, using exponential response characteristics. In the experimental work operators were asked to track a moving target.

Conklin found that their tracking accuracy dropped rapidly as the dynamic lag was increased. The operators' performances reached a level of chance behavior for dynamic lags of over a few seconds. He also compared the effects of dynamic lags on pursuit and compensatory tracking, and showed that pursuit tracking is superior to compensatory tracking.

In 1949 Warrick (4) reported on his studies of system delays resulting from signal transmission lags of up to 320 milliseconds. The study was made with a compensatory tracking system. Warrick was studying the hypothesis that tracking error is linearly related to the amount of the signal transmission lag. The linear relationship did not appear as anticipated, but his work did show that tracking ability deteriorates rapidly as the length of the signal transmission lag is increased.

A great deal of value is obtained from tracking experiments conducted in laboratories. The tracking problem, however, is presented in the comparatively clean fashion of a simple target represented by a moving spot or moving line. The situation in a real mission will involve a television picture of a landscape. Tracking information will be presented in a more vague and confusing way than in laboratory presentations. Extraneous information can be obtained from television pictures and may confuse, or at least distract, the human operator. Furthermore, target presentation is influenced by past tracking performance. If the operator's driving has been faulty, he obtains a different view of the tracking problem than if his tracking had been better. In an effort to simulate real missions more closely, several investigators have used robot vehicles in field tests. These vehicles were equipped with television cameras.

One of the first to use an actual vehicle was Adams (1,2), who conducted a series of tests in 1961 involving signal transmission lag with the vehicle dynamic lags kept to a minimum. In field tests a robot vehicle was driven with various combinations of speeds up to 2.7 feet per second and signal lags up to 3 seconds. Scoring was achieved by measuring the percentage time that a circular disc 16 inches in diameter and located directly under the center of the vehicle was kept above a white line drawn on the test field. Scoring is presented in the form of percentage time-on-target. Both two-wheel and four-wheel steering were used. The two-wheel steering is the conventional automobile configuration. Four-wheel steering is different in that all four wheels are turned together beneath the body of the vehicle. A four-wheel type vehicle is used in the present study. An important point to consider, here, however, is the fact that four-wheel steering produces a more highly maneuverable vehicle than can be obtained with two wheel steering.

Adams compared the tracking performances of two-wheel and four-wheel steering configurations on different courses. Each course was designed to make use of the maximum maneuverability permitted for the type of steering used. The time-on-target scores were similar. Since the four-wheel vehicle was driven over a more difficult course, it was concluded that four-wheel steering permits better control than two-wheel steering when signal transmission lags are present in the feedback control system.

As an example of the rapid deterioration of tracking ability with increasing signal transmission lag, the following percentage time-on-target score was obtained for a four-wheel configuration and a vehicle speed of 2.7 feet per second:

98%	with	0 seconds signal transmission lag
85%	with	½ seconds signal transmission lag
55%	with	1 second signal transmission lag
25%	with	2 seconds signal transmission lag

Another study using a robot vehicle was conducted by the Grumman Aircraft Company (5). In their work a two-wheel or automobile type of steering was used to study the effects of signal transmission lag on human tracking performance. In the experiments that have been published to date, a modified Jeep was driven at average speeds of 1.82, 2.74, and 4.33 mph, and a signal transmission lag of 2½ seconds was used. Three different course complexities were used, and each course was lined with traffic cones set 12.5 feet apart. Whereas Adams asked his test drivers to follow a white line, Grumman asked their drivers to stay within test roads outlined by traffic cones. Both tasks involve tracking.

For a given signal transmission lag Grumman's results show a deterioration in tracking ability that is reported as being "exponentially" related to increasing vehicle speeds. As an example of results, the percentage of traffic cones hit at a given trial for the most difficult course was:

18%	at	2.1 mph
31%	at	3.2 mph
35%	at	4.7 mph

All values were obtained with the signal transmission lag of 2½ seconds. Grumman's results also showed that the scores were dependent on the complexity of the course.

Both the Grumman and the Adams studies were conducted with full-size vehicles. The Airborne Instruments Laboratory (6) has developed a 24'x15' scale model of a "lunar landscape." Their test vehicle consists of a television camera which is mounted on a set of tracks and is 14"x8"x15" in size. Driving speeds were scaled so that one vehicle length of travel per second for the scaled model is considered equivalent to one vehicle length for a full-size vehicle. In their tests, drivers were asked to steer the model robot vehicle from a given starting point to a distant goal. The route followed was chosen by the operator. Obstacle sizes ranged from ½ to 5 times the model vehicle's height. The distant goal was periodically lost to view during a given run. Scores were made by measuring the length of time required to reach the goal and by counting the number of obstacles hit en route. One advantage of this approach to the problem of studying control when there are signal transmission lags present is that the sharp, dark, and light contrasts of lunar lumination can be approximated by proper lighting of the model lunar landscape in combination with the correct television lens settings. No numerical results are presented in the available reports(6).

All these studies indicate that tracking ability is seriously impaired by the presence of signal transmission and dynamic lags. Tracking ability deteriorates for given signal transmission lags as the vehicle speed increases. Likewise, there is a decrease in tracking skill for a given speed when the signal transmission lags are increased. Hence, increasing combinations of vehicular speed and signal transmission lag contribute to the diminishing of tracking ability. In those situations where a signal transmission lag is unavoidable, a human operator has no choice but to drive slowly in an effort to maintain reasonable control.

There is no exact place where tracking ability is lost, but rather a continuing decrease in ability as speed and signal transmission lags are increased. Just what is acceptable depends on the local conditions facing the robot vehicle. The task confronting the human operator when system delays occur can be visualized by reviewing the tracking problem with which he is faced. In order to perform pursuit tracking, the human operator must be able to observe the difference between his intended path of travel and the actual performance of the tracking vehicle. His objective is to make the displacement error signal between the two satisfactorily small.

By watching a television picture of the approaching landscape, a human operator is able to maintain a route to follow. He should have little difficulty in finding a route to follow if the television picture is of good quality. The difficulty occurs when he tries to observe the behavior of his tracking robot vehicle. If system delays are present, he does not have an indication of where the vehicle will be on the landscape after it has responded to all steering commands currently being processed through the delay. He does not have a displacement error signal that he can try to minimize. If he uses the information provided on the television picture without modification, he will be working with a displacement error that is obsolete and does not include the effects of the instructions currently being processed. This would obviously lead to faulty driving. In trying to obtain a valid displacement error signal, the operator must know where the vehicle will be on the landscape when it can be reached and influenced by a new command that he is planning to send. He must make a mental prediction of where the vehicle will go as it responds to the information that has been sent but whose effects have not as yet been reported via television feedback.

In forming a mental prediction, the operator must remember all the instructions that have been sent, but for which no feedback has been received. He must continually revise this list as new instructions are added and old ones deleted. He has to consider the changing influence of each command as it moves through the list. He has to use this ever-changing library of information to form a continuous set of prediction calculations. This is a formidable task. The data shown in the experimental studies that have been quoted show that it is beyond human ability to perform these calculations successfully when system delays and vehicle speeds are appreciable.

These studies (1) - (6) show that signal transmission lag, dynamic lag, and vehicle speeds contribute to the deterioration of tracking ability. For a given speed, increasing the signal transmission lag means decreasing tracking ability. Likewise, for a given signal transmission lag, increasing vehicular speed results in poorer tracking. If a remote control vehicle is so located that a signal transmission lag is unavoidable, the only way to make precise maneuvers is to drive slowly. Unless one is content with slow speeds (less than 2 mph for a lunar vehicle) when complicated driving situations are encountered, a means must be found for making prediction calculations more accurately than a human being is capable of doing. This can be done with a predictor, such as the one that is developed in this project.

E. BACKGROUND WORK IN THE DEVELOPMENT OF PREDICTOR SYSTEMS

A search of the literature disclosed several predictor developments that are pertinent to the present study.

In 1954 Zieboltz and Paynter (7) presented a paper in which they discussed the possibilities of improving control by the use of a compressed-time scale computer. This work was intended for automatic control systems where a human being is not present in the control loop. The compressed-time scale computer performs rapid calculations and looks into the future to see how the controlled device will behave as it responds to system inputs. Two time scales are involved. The first time scale involves the rate at which the controlled device responds to input commands. This time scale can be identified as a real-time scale. The other time scale can be identified as a compressed-time scale using the rate at which the compressed-time computer performs its prediction calculations.

In Zieboltz and Paynter's development, a compressed-time scale computer is placed in the control system feedback loop. In this way the predictions formed by the compressed-time scale computer are used to modify the system inputs. The long range consequences of inputs are considered and used to reshape the inputs to obtain the desired system outputs.

The idea of feeding prediction information back into the control system can be extended to systems where a human operator is part of the control loop. The term prediction instrument (8) - (10) is used to designate those devices which present prediction information to the human operator to help him on his control task.

Prior to the present work, no predictor instruments have been built for use where there are long signal transmission lags. However, prediction instruments have been considered for cases where there are long dynamic lags. The primary emphasis has been on the development of predictor instruments to aid in controlling the diving performance of submarines. A large vessel of this type responds slowly to commands, and there is danger that the man who controls the diving planes may over-control and cause the vessel to dive below the desired depth. In addition, hunting about the desired depth may result as the operator tries to predict the submarine's eventual response to his diving commands. Ideally, the submarine should be controlled to reach the desired depth without over-shooting.

The problems of prediction when there are long signal transmission lags have several things in common with the prediction problem for submarines where there are long synamic lags. Both systems need an input device for the human operator, a computing device for calculating predictions, and a means for displaying prediction information to the operator. Both systems involve a consideration of the man-to-machine and the machine-to-man interfaces. The major human factors problem involves the machine-to-man interface and the way in which the prediction information is displayed for the benefit of the human operator.

F. THE HUMAN IN THE SYSTEM

Throughout this project we are following the policy of using man where he is superior to machines, and using machines where they are superior to man. Man does play an essential role in the remote control of the robot vehicle. Unknown landscapes will be presented to the human operator through the view of the television display. The amount of information being processed is very large and of a vague nature. The human operator is needed to select pertinent information from a background of information that is not of value to the tracking task. It is likely that man's experience with the topography of the earth will be helpful in tracking on the moon or one of the planets. Man is essential in coping with the unexpected situations that will undoubtedly arise. His ability to choose between alternatives is an important consideration. Not knowing in advance what types of alternatives may present themselves, it is impossible to program a computer alternative to make these decisions for man. Man's ability to make observations extraneous to the actual tracking role and his ability to recognize the significance of unrelated events may yield important dividends in the actual mission.

In our experimental arrangement, the human operator is given a predictor display, thereby freeing him from the task of having to make mental prediction calculations. The television camera on the test vehicle uses a wide angle lens to present a wide viewing angle to the operator. The vehicle steering is one of the simplest possible forms using a displacement control where the direction of travel of the vehicle is directly related to the angular position of the input steering wheel. The human operator's task is to observe a television view of the landscape that the robot vehicle is approaching, to focus his attention upon the steering of the prediction marker superimposed on the picture, and to introduce steering commands through the action of turning a steering wheel. All other tasks in the system are handled by machine.

CHAPTER II

DEVELOPMENT OF THE EXPERIMENTAL CONTROL SYSTEM

A. INTRODUCTION

The purpose of the predictor is to aid the human operator in his task of controlling a robot vehicle when long signal transmission lags appear in the control system. The predictor achieves this goal two ways. First, it relieves the operator of the burden of having to perform mental calculations for determining a prediction of vehicular behavior. Second, it presents the prediction information to the operator in a useful and effective manner. The details of the predictor are considered in this chapter.

The predictor is one part of the overall control system built for this experimental study. Fig. 4 shows the breakdown of the control system. It shows that the control system consists of two basic parts: the robot vehicle and the control station. The control station is further divided into the steering loop and the predictor. The steering loop is needed regardless of whether a predictor is used. It represents the means by which steering instructions originate, the way in which the signal transmission lag is introduced, and the method of displaying a television picture showing the vehicle's direction of travel. When prediction is desired, the predictor is added at the control station.

The predictor, however, does not stand as an isolated unit in the control system or even in the control station. The steering loop, the predictor, and the robot vehicle are all inter-related. Design decisions for any one of these units are influenced by resulting effects on the other two units. The steering loop and the predictor even share some of the same equipment. Hence, it is not valid to describe these units separately; instead, it is necessary to study them together and to consider the ways in which they are inter-related.

B. THE TEST VEHICLE

The robot vehicle used in the present study uses a four-wheel steering where all four wheels turn together underneath the body of the vehicle. Fig. 5 represents a comparison between four-wheel and the familiar two-wheel steering found in automobiles. Four-wheel steering leads to a highly-maneuverable and responsive vehicle. A unique feature of the vehicle is that its body does not change orientation when the vehicle changes direction. Consequently, there is no forward direction save that in which the wheels are pointed. In order to look forward, the vehicle's television camera turns with the wheels.

The wheels are steered by indexing stepping motors. The com-

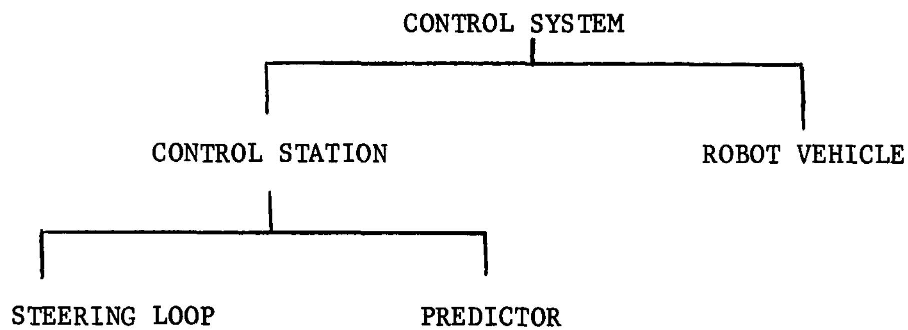


Fig. 4 CONTROL SYSTEM BREAK-DOWN

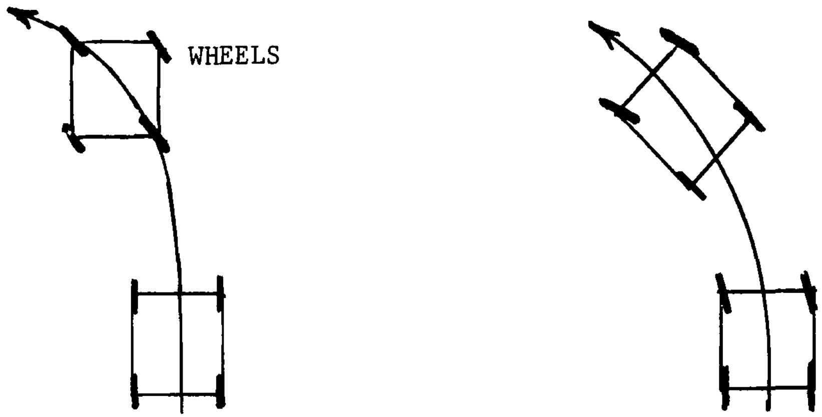


Fig. 5 FOUR-WHEEL VERSUS TWO-WHEEL CONFIGURATION

mercially available stepping motors make 200 steps per revolution. Since these motors step without cummulative error, no feedback system is needed on the vehicle to control the magnitude of each step.

The steering behavior of both a four-wheel and a two-wheel vehicle are shown in Fig. 6. The steering characteristics with the two-wheel vehicle are more involved than with the four-wheel vehicle. With two-wheel steering, the vehicle spirals into a turn, may continue on an arc, and then spirals out of the turn. With four-wheel steering, the turn is completed with each step of the stepping motors used for steering. The angular turns for four-wheel steering are grossly exaggerated in Fig. 6. In reality the 45° change in direction shown requires 25 individual steps.

The vehicle receives its steering instructions through a radio link. The instructions are coded in the form of AC pulses, with 960 cps and 1390 cps signals arbitrarily selected for left and right steps respectively. Pulses are sent at a maximum rate of 15 pulses per second. The wheels are geared directly to the stepping motors, so that 200 steps in a given direction complete a 360° turn for the vehicle. The turning radius is a function of the pulse rate and the vehicle's speed, and is expressed approximately as $R = pv/2\pi n$, where n is the number of pulses per second, p is the number of steps per revolution, and v the vehicle speed. As a specific example for this system, with $n = 15$ pulses per second, $p = 200$ steps per revolution, and $v = 7.1$ feet per second, $R = 15.1$ feet.

The steering pulses originate in a steering box. When the steering wheel is turned, pulses are produced to cause left or right turns. The steering wheel is governor-controlled so that pulses can not be sent at a rate greater than 15 pulses per second. An angular displacement of the steering wheel results in an angular displacement of the vehicle's stepping motors, and hence an angular displacement of the vehicle. When making a turn, the steering wheel is rotated through the appropriate angle and then left in the new position. After one delay period (equal to the total signal transmission lag), the television picture will show the vehicle making a similar change in direction.

In establishing the desirable maneuverability of the vehicle, the viewing angle of the vehicle's television camera and the length of the signal transmission lag must be considered. These relationships are shown in Fig. 7. The television camera is equipped with a wide angle lens that permits a horizontal angle of vision of 53°. With the given maneuverability, the vehicle can be driven outside of the television viewing angle for signal transmission lags exceeding 2 seconds. For the lunar example with a total signal transmission lag of 2.6 seconds, the vehicle can be driven so that the prediction marker will move outside of the television picture. As a result, the viewing angle of the television camera on the vehicle is the limiting factor, and there is

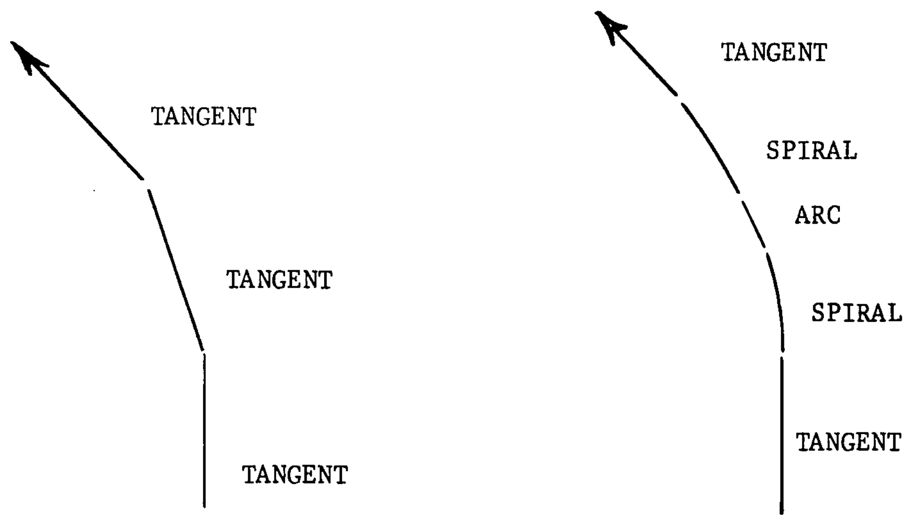


Fig. 6 FOUR-WHEEL VERSUS TWO-WHEEL STEERING

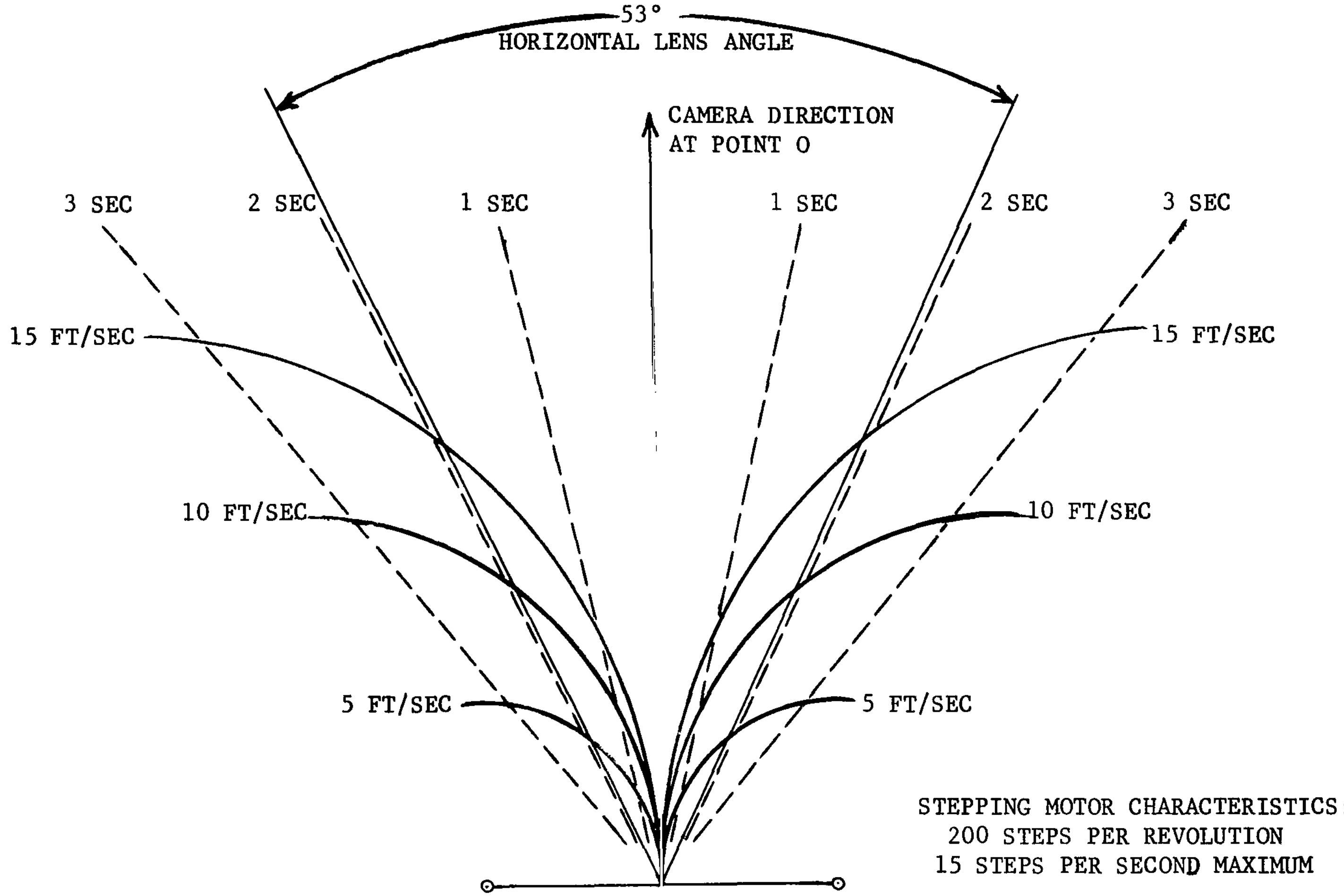


Fig. 7 CURVES OF MAXIMUM VEHICLE MANEUVERABILITY
VERSUS TIME DELAY AND CAMERA ANGLE OF VISION

no point in designing a vehicle that is more maneuverable than the present one.

The camera is mounted so that it looks forward horizontally or can be depressed to see the ground closer to the vehicle. The crucial need is for the ability to see the ground where the marker will be superimposed on the television display in the control station. The prediction length, or the distance by which the marker leads the vehicle, is a function of the vehicle speed and the magnitude of the signal transmission lag. These relationships are shown in Fig. 8. The important items on the test vehicle are shown in Figs. 9 and 10.

Fig. 11 shows the way in which the stepping motors are advanced. Each motor contains four coils which may be identified as A_1, A_2, B_1, and B_2. At all times one A coil and one B coil are energized. Stepping is achieved by switching the A and B coils in the sequence shown in the illustration. Four combinations of A and B coils are possible, and these are repeated 50 times for one complete rotation of the motor. Fig. 11 also shows a block diagram of the steering components for the test vehicle. After the steering pulses are received by the radio, they go to filters where the 960 cps left turn signals are separated from the 1390 cps right turn signals. These pulse signals are then sent to a steering logic system. The output of the steering logic board controls three separate pairs of driver flip-flops for the proper stepping of the three motors.

The use of stepping motors represents a unique feature of this design. Since radio control signals are best sent as pulses to avoid noise difficulties, the use of stepping motors provides a steering means that makes direct use of the control pulses. As already mentioned, stepping motors do not require any feedback control checking because of their steps which advance without cumulative error to within 0.09° of each index position.

A wiring diagram of the test vehicle is shown in Fig. 12, and further details of the test vehicle appear in Appendix B.

C. CONTROL STATION

The control station block diagram is presented in Fig. 13, where the equipment used by both the steering loop and the predictor are shown together. This is a necessity because several of the blocks are shared by both units. Figs. 14 and 15, however, are extracted from Fig. 13, and show separately the blocks that are used by the steering loop and the predictor.

These illustrations show that the steering loop starts with a steering box where pulses are originated as the steering wheel is turned by the human operator. The box contains two telephone dial assemblies. These assemblies contain cams which operate switches to

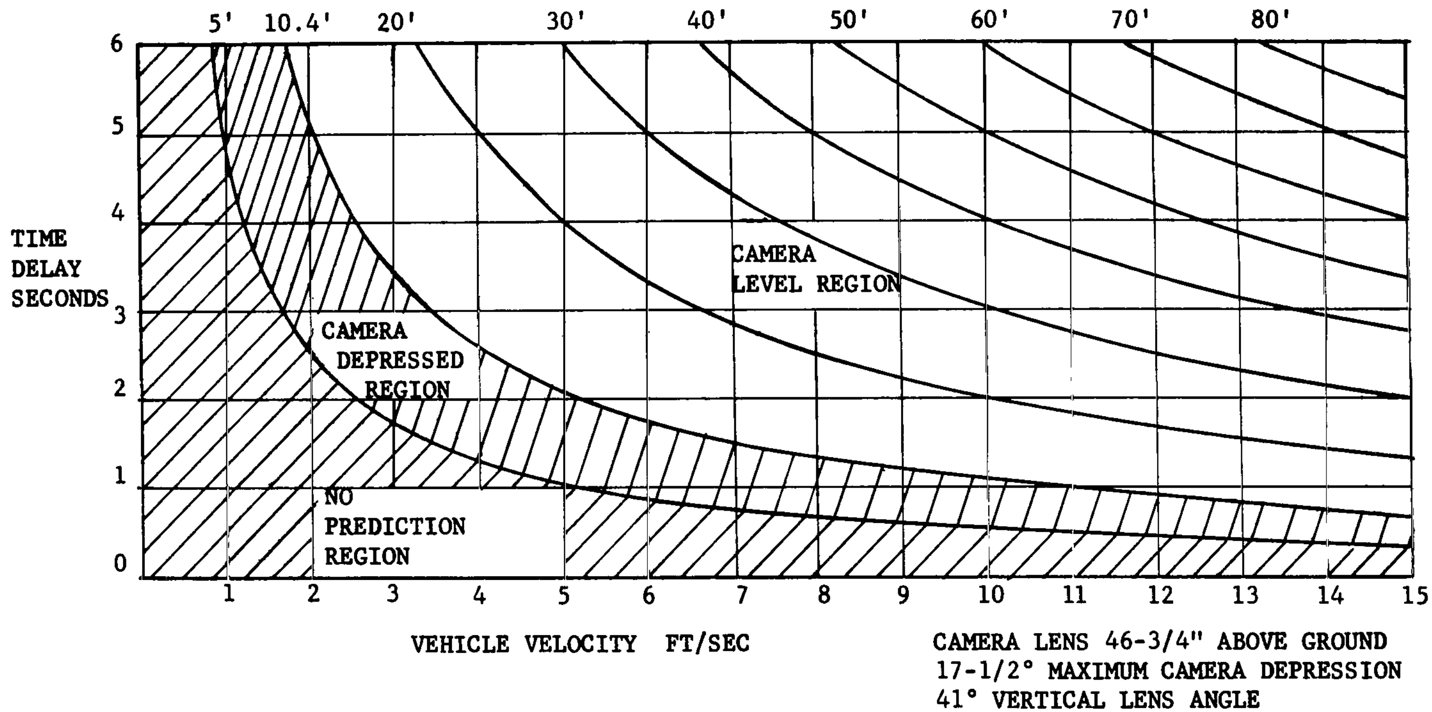


Fig. 8 PREDICTION REGIONS

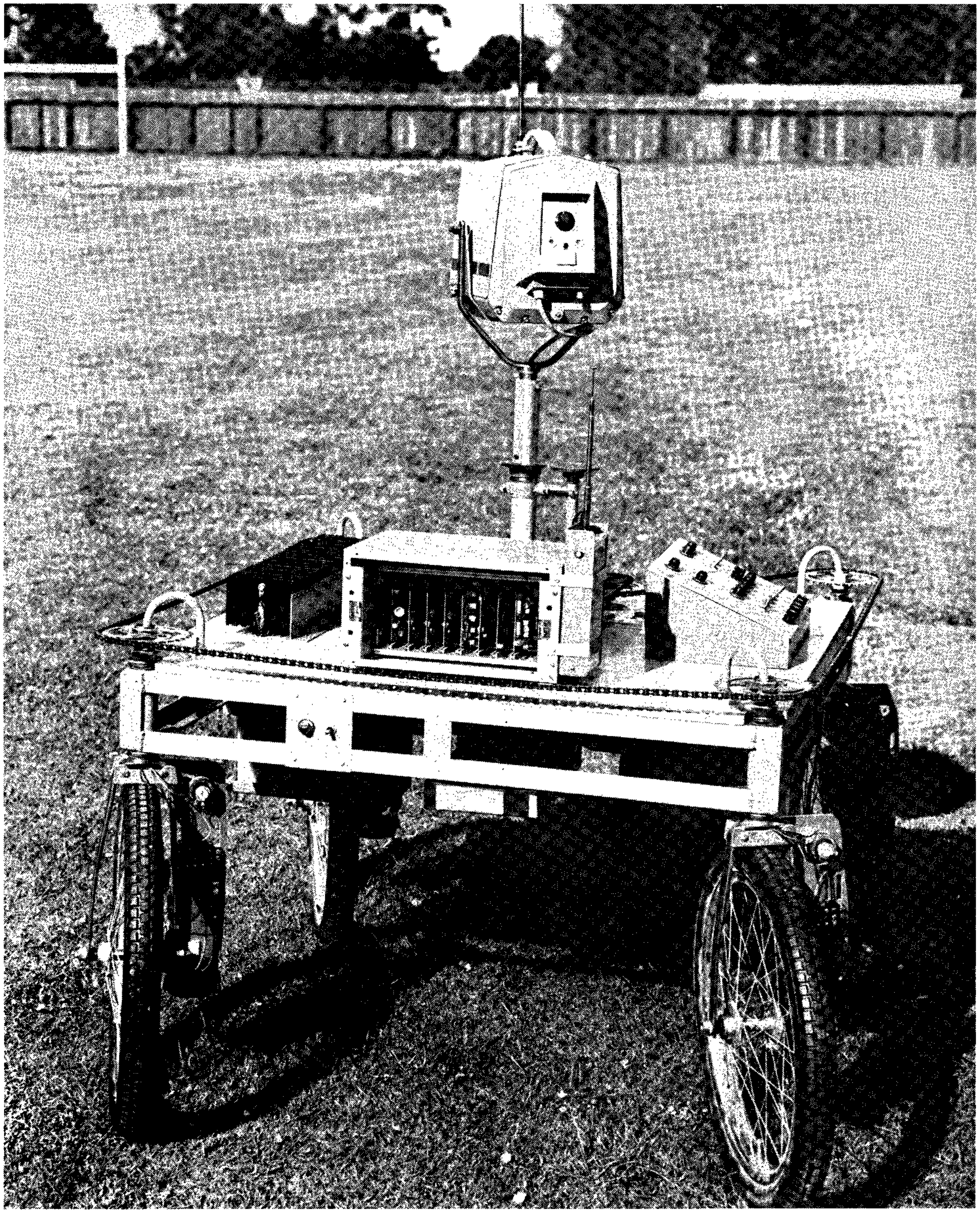


Fig. 9 VEHICLE - GROUND VIEW

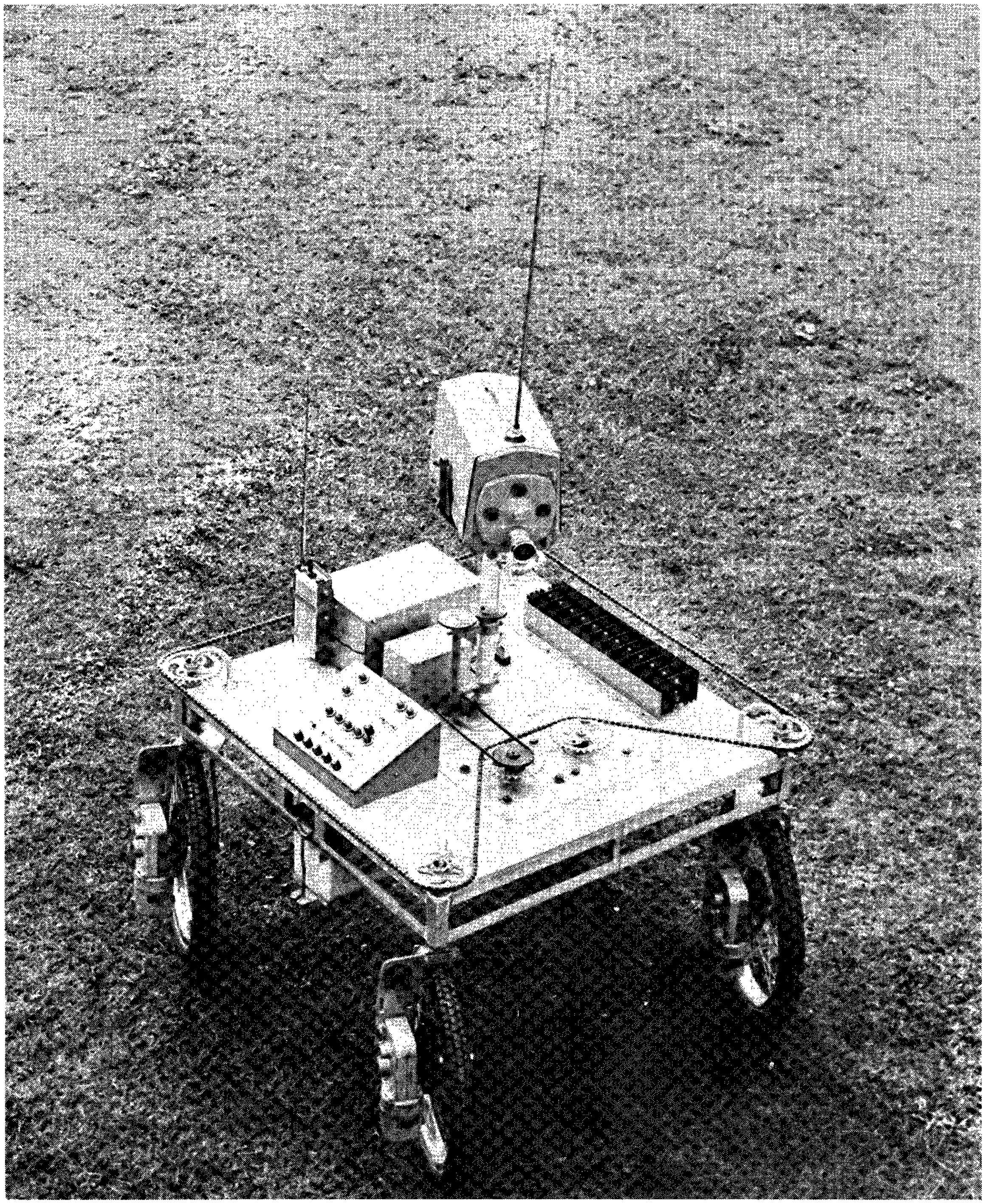


Fig. 10 VEHICLE - AERIAL VIEW

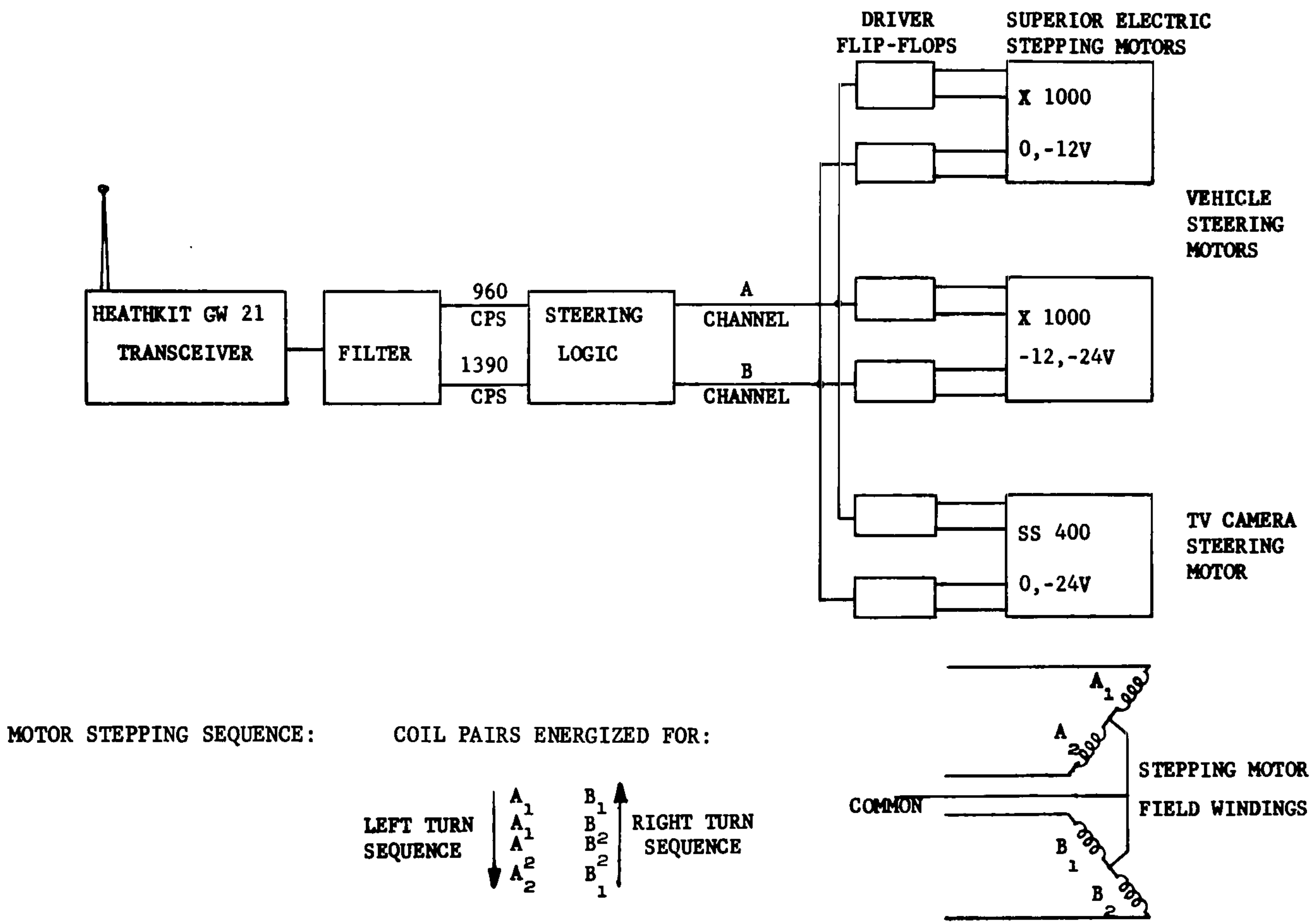


Fig. 11 VEHICLE STEERING BLOCK DIAGRAM

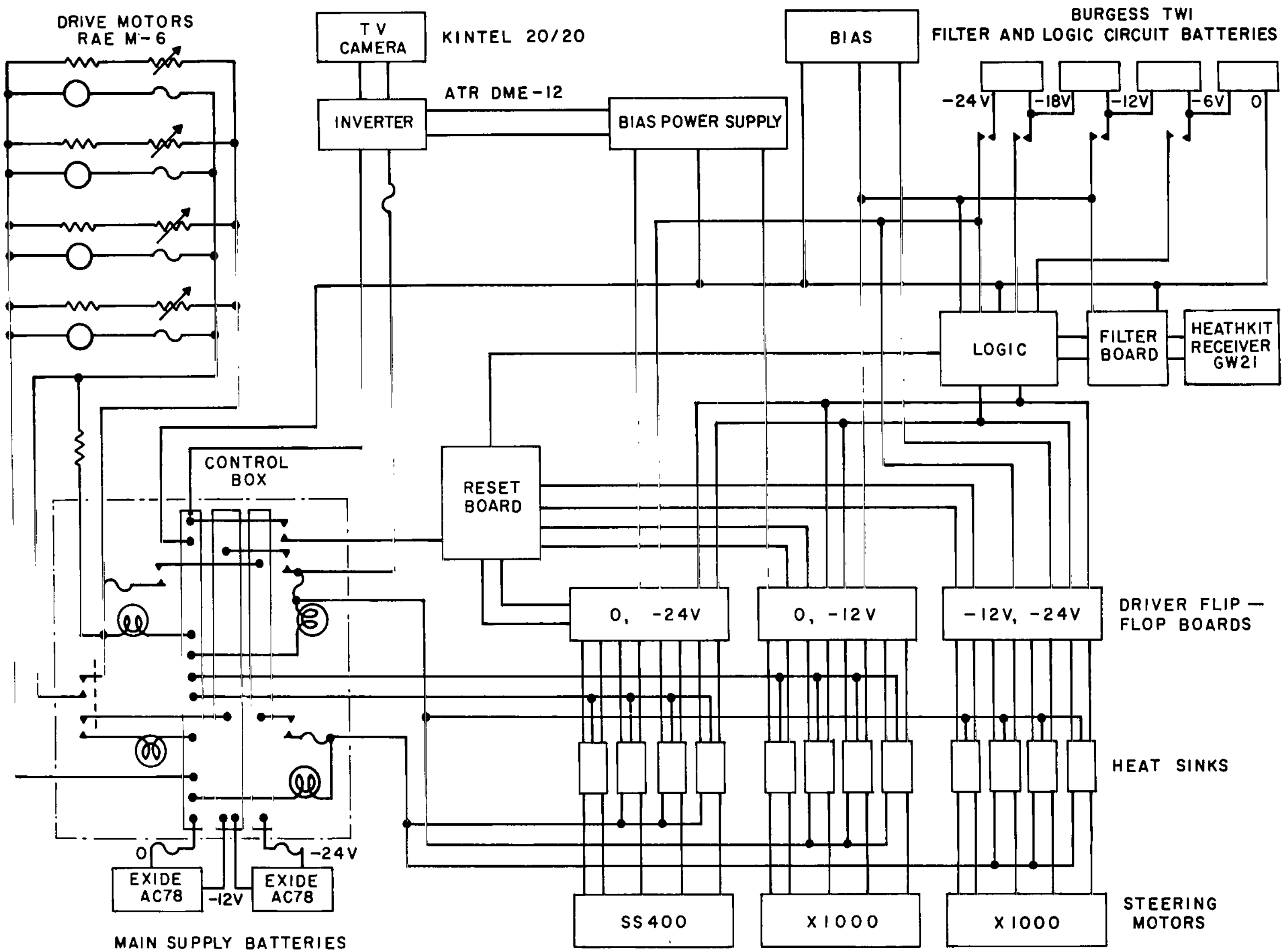


Fig. 12 VEHICLE WIRING

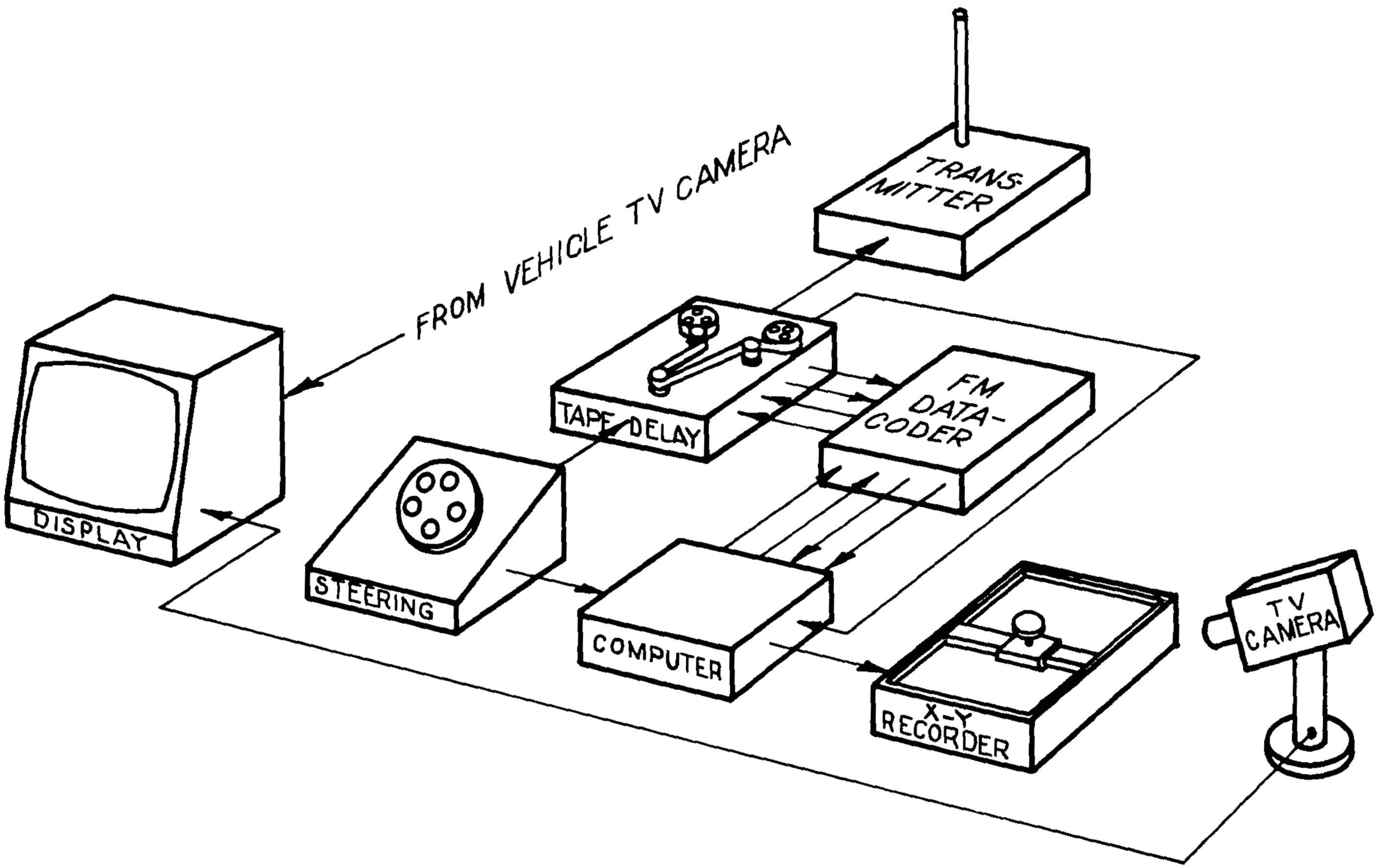


Fig. 13 CONTROL STATION BLOCK DIAGRAM

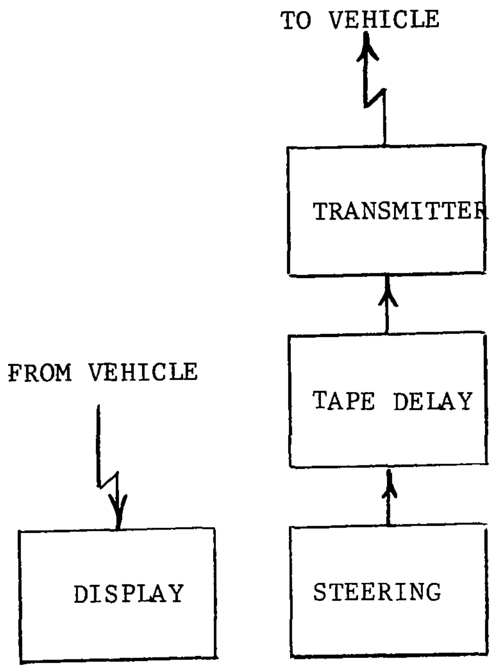


Fig. 14 CONTROL STATION STEERING LOOP BLOCK DIAGRAM

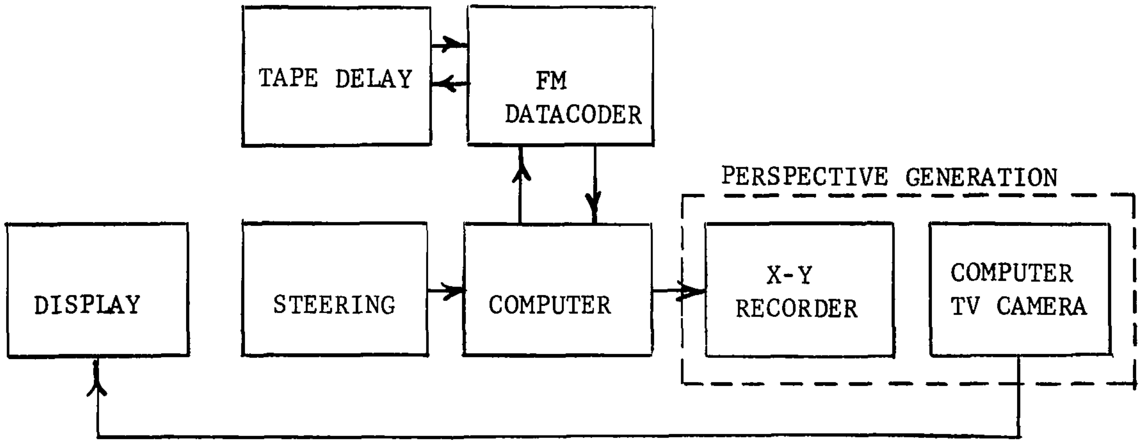


Fig. 15 CONTROL STATION PREDICTOR
BLOCK DIAGRAM

produce steering pulses. The dial assemblies are equipped with overrunning clutches so that one assembly is operative when the steering wheel is turned in one direction, and the other assembly is used when the steering wheel is turned in the opposite direction. The dial assemblies are governor-controlled so that the pulse rate can not exceed 15 pulses per second. This "keys" the steering wheel to the vehicle so that the steering wheel can not be turned faster than the vehicle can respond.

The steering loop also uses a tape recorder for simulating the signal transmission lag, a transmitter for sending the steering pulses to the vehicle, and a television monitor for displaying the television pictures that are sent back to the control station from the vehicle.

The predictor components are also shown in Figs. 13 and 15. These illustrations show that duplicate steering pulses go to a computer where prediction calculations are performed. The computer also makes use of the tape recorder for simulation of signal transmission lag. The reasons for using the tape recorder are explained when the computational procedure is discussed. At this point, the need for the block identified as the FM Datacoder is also explained. The output of the computer is in the form of voltages describing a plan view of how the prediction marker leads the test vehicle. This information can not be directly superimposed on the television picture from the vehicle. It must first be converted from plan view information to a form that matches the perspective of the vehicle's television camera. The perspective generation equipment consists of an X-Y recorder and a computer television camera. A circular marker is mounted on the pen holder of the X-Y recorder. The television camera views the marker moving around on the X-Y recorder with a perspective similar to the way in which the vehicle's television camera surveys the vehicle's field of action. The two pictures are then superimposed on the single monitor in the control station to give the illusion of an elliptical marker or symbolic vehicle moving across the landscape in advance of the robot vehicle.

The X-Y recorder and the computer television camera form a unique combination for generating perspective. The combination offers a great deal of flexibility. For example, the size and shape of the prediction marker can be changed by simply changing the marker on the X-Y recorder. If desirable, a scaled model of the robot vehicle could even be used. This might form a more realistic prediction on the television display than the elliptical marker presently in use. The X-Y recorder and the computer television camera also provide the break in the predictor where corrections for pitch and roll can be added. The important point is that the prediction marker must appear to travel over the surface of the ground. If the surface appears to move about as the vehicle pitches and rolls over rough terrain, the prediction marker must be given a similar motion. By using feedback information from the vehicle describing the pitching and rolling characteristics of the vehicle, a similar action can be given to the computer television camera. In this way, the marker can be "tied" to the surface over which it appears to be moving.

The video output of the computer television camera is not sent directly to the television monitor. It goes first to a Schmitt Trigger where the variable video output of the camera is converted to a digital basis where either nothing or a fixed signal is sent on to the television monitor. The X-Y recorder is darkened so that only the marker is illuminated. As a result, signals reach the television monitor describing the shape and motion of a marker that apparently moves in a total void. When two television pictures are superimposed on the television monitor, no ghosting can occur anywhere except where the marker appears. Here, however, the intensity of the marker can be adjusted so that it blocks out the landscape features.

Ghosting becomes a problem only when the human operator drives the marker around behind obstacles on the landscape. Instead of disappearing from view, the marker shines through and dominates the scene. Unless the operator is careful to watch the marker driving around behind obstacles, he will experience the sensation of seeing the marker appear in front of the obstacle.

The X-Y recorder and the computer television camera arrangement is shown in Fig. 16. A circular marker is mounted on the pen holder of the recorder, and two replacement markers of different sizes are shown in front of the recorder. This photograph was taken before the X-Y recorder was darkened. In use, the bright areas of the recorder are covered, the entire assembly is mounted in a darkened place in the control station, and the shiny marker is illuminated by a light mounted above the unit.

Figs. 17 through 22 are photographs showing the arrangement of the control station. The control station equipment is mounted in a small panel truck. The area that is used by the human operator during tests doubles as an area for carrying the test vehicle to and from the field site where experiments are conducted.

Fig. 18 shows the operator using the equipment. Normally, the operator sits directly in front of the monitor and the steering box is mounted in front of and slightly below the monitor. With the operator sitting to one side in the photograph, it is possible to see the way in which the prediction marker appears superimposed on the television view of the test field. A white line used for tracking experiments can be clearly seen in the television picture. Unfortunately, it was necessary to open the back doors of the truck when taking this photograph. The resultant glare on the face of the television monitor is not present when the doors are closed and the equipment is in use.

This collection of photographs ends with an overall view of the control station and the vehicle. Fig. 22 shows the truck and the test vehicle on the field where experiments are conducted. The

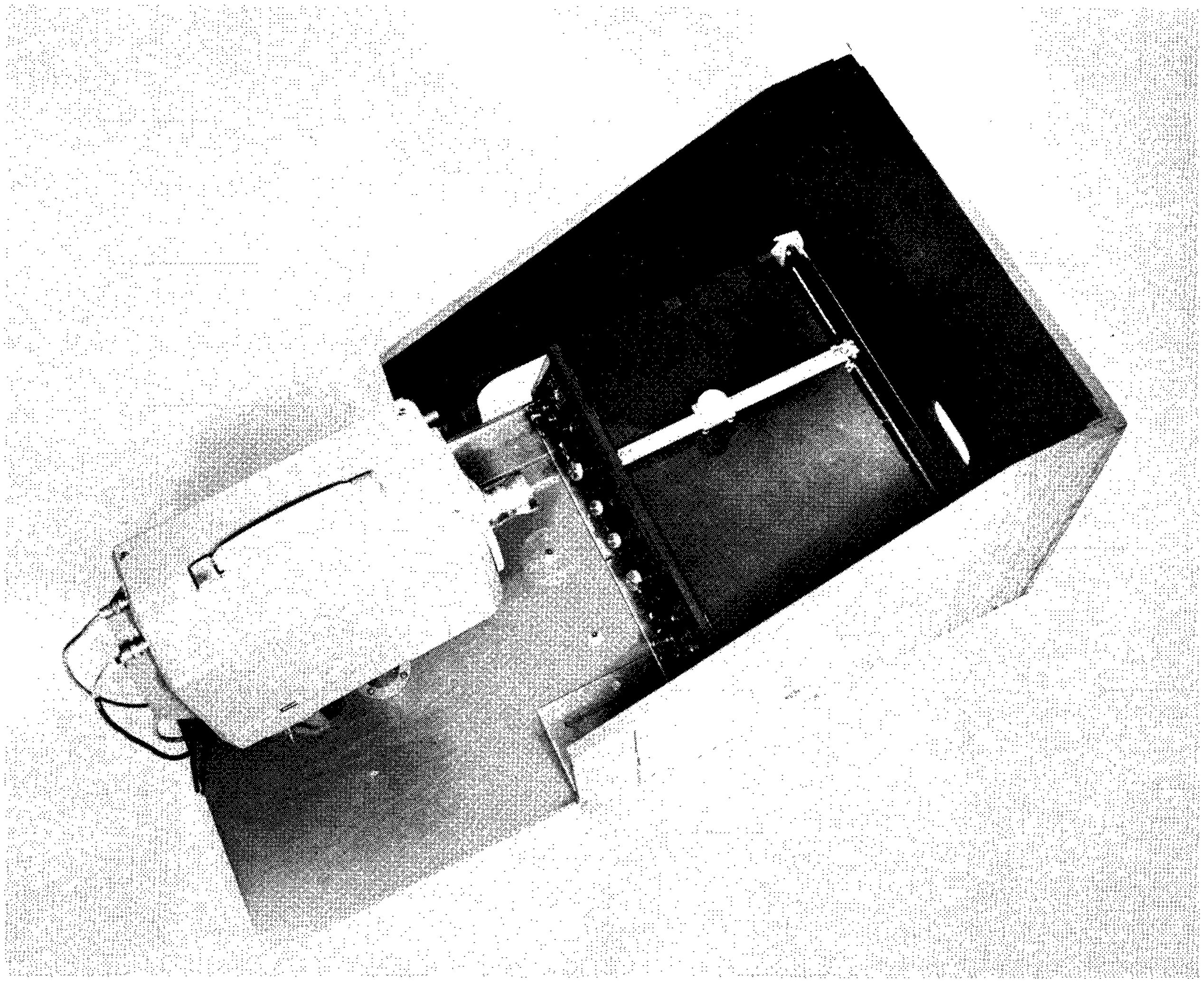


Fig. 16 X-Y RECORDER AND COMPUTER TELEVISION CAMERA

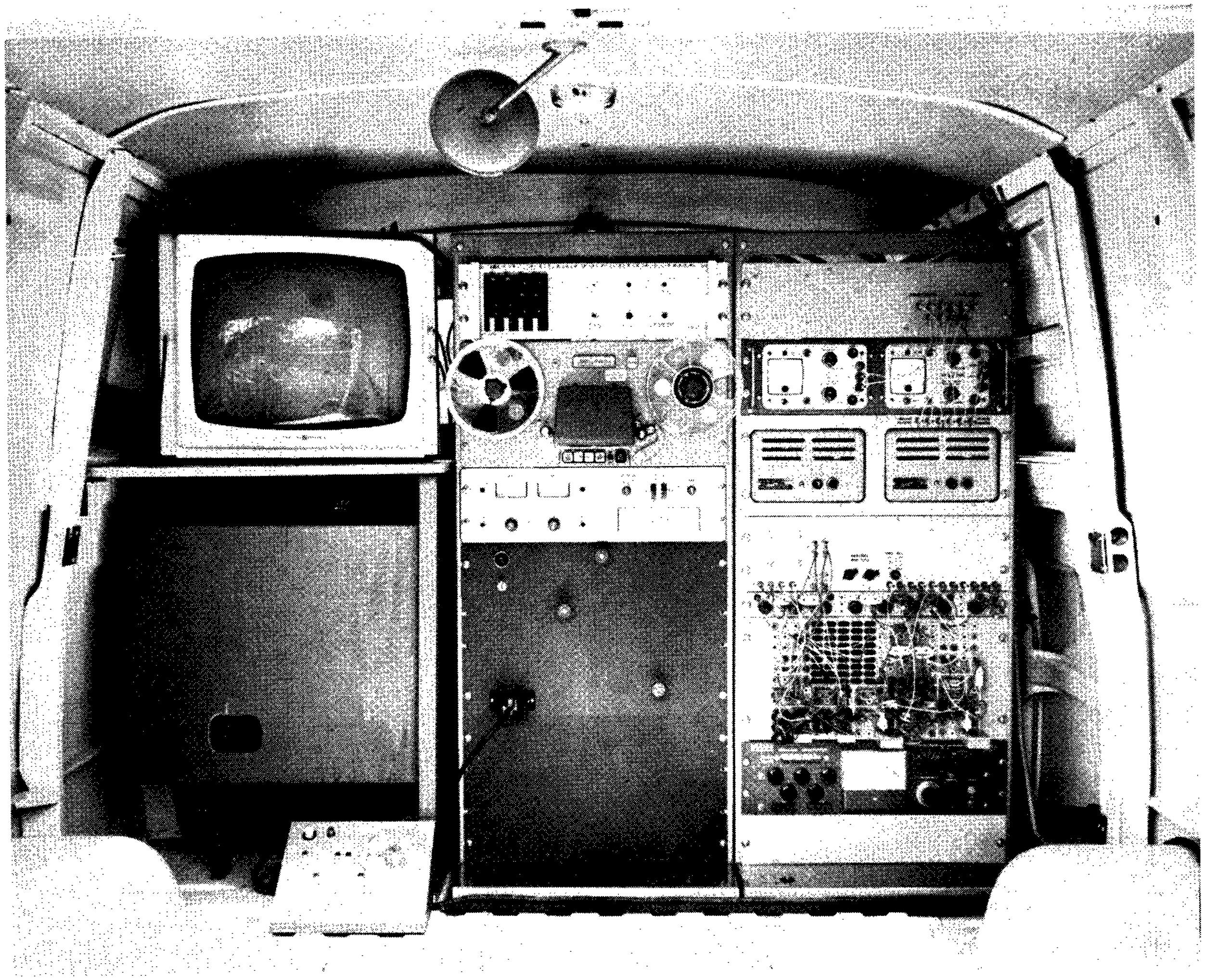


Fig. 17 CONTROL STATION

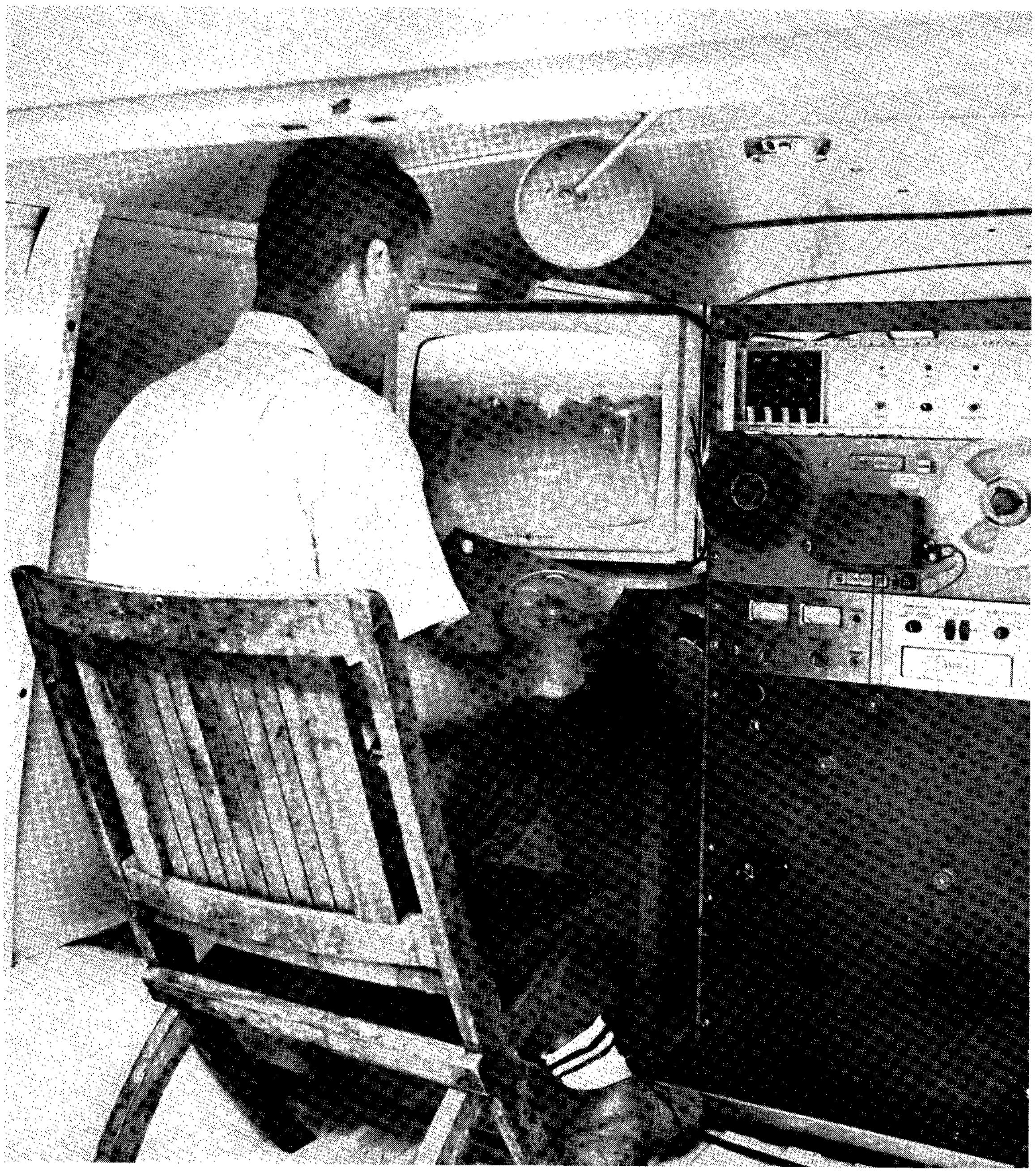


Fig. 18 **DRIVER VIEW**

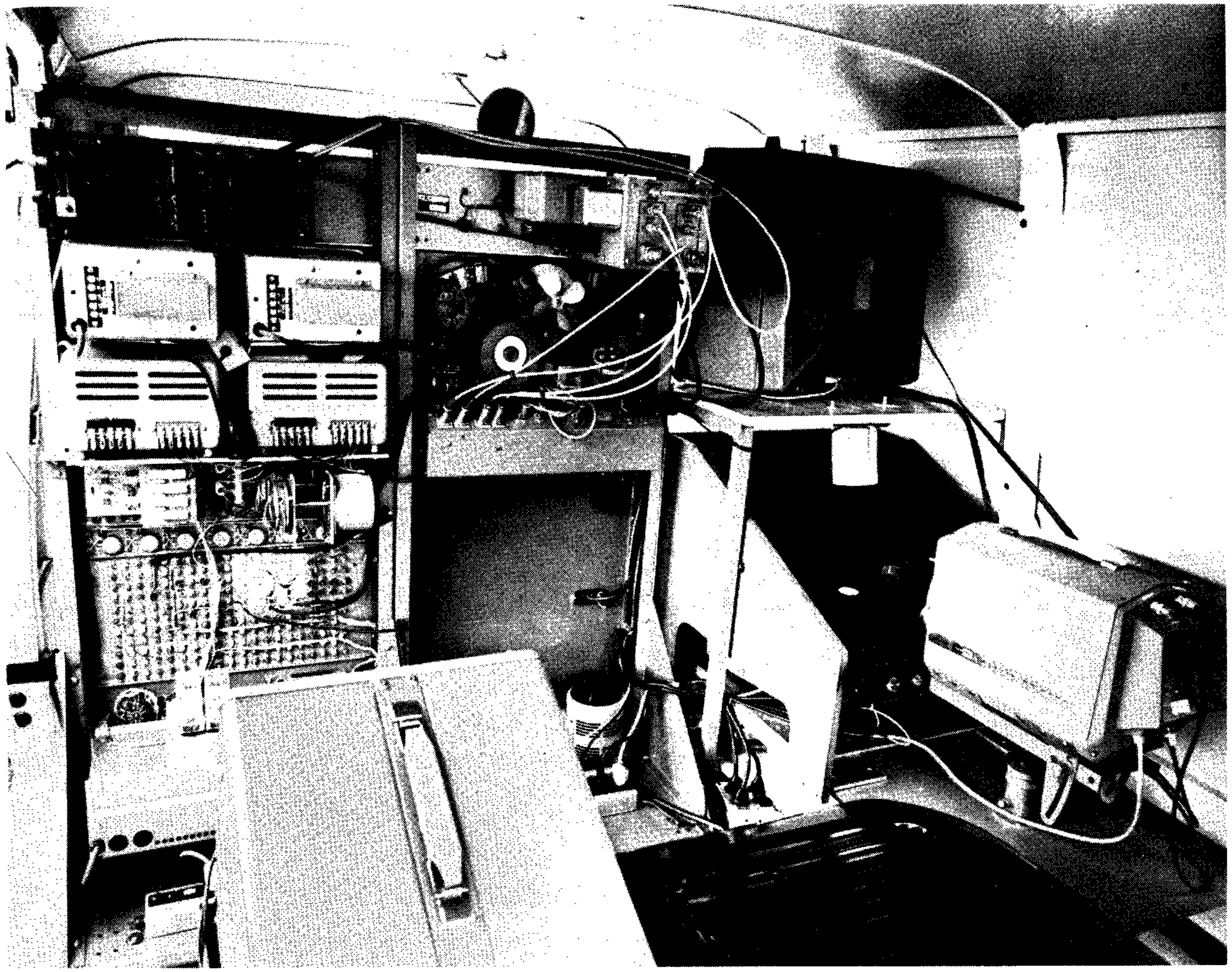


Fig. 19 CONTROL STATION - REAR VIEW

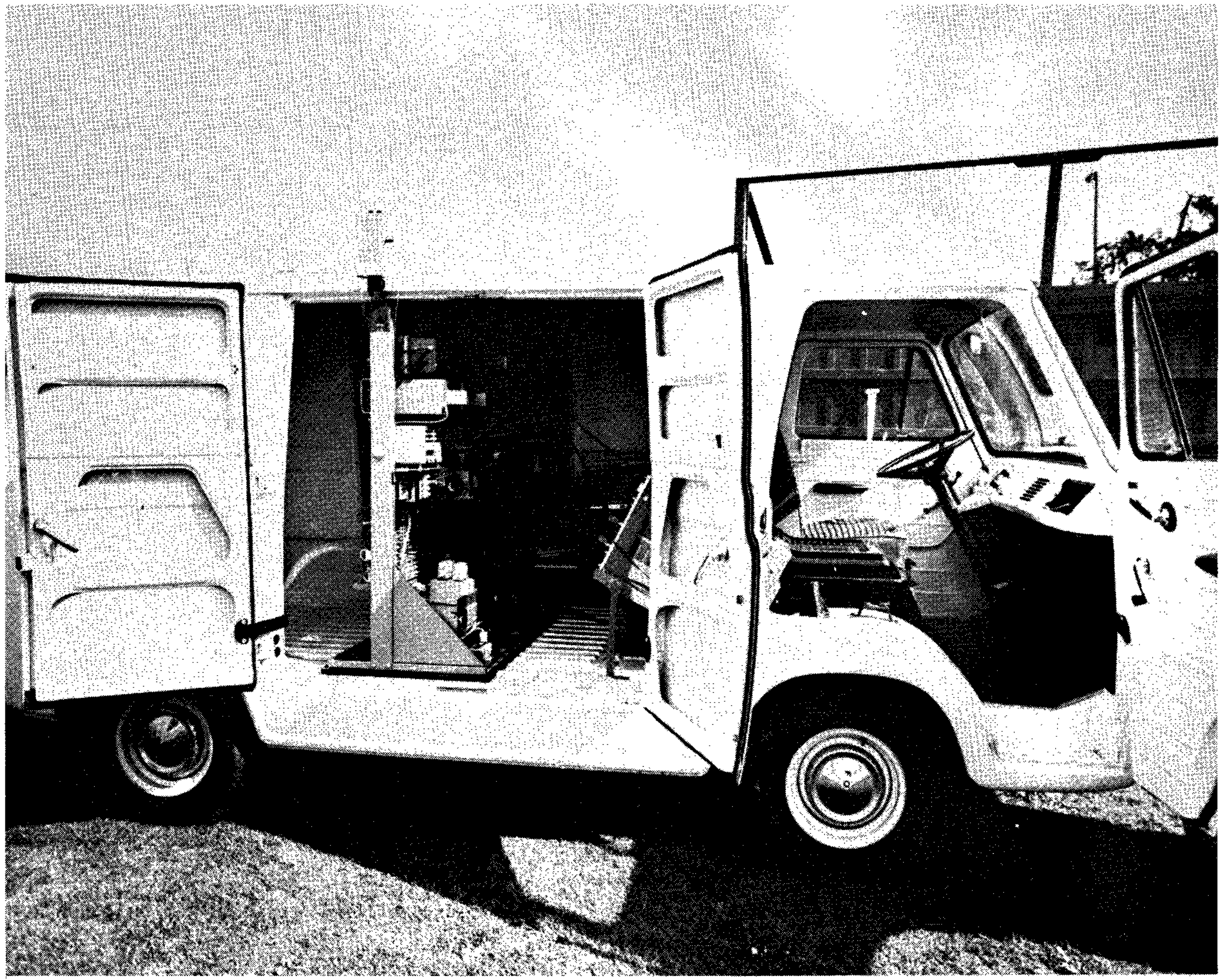


Fig. 20 CONTROL STATION - SIDE VIEW

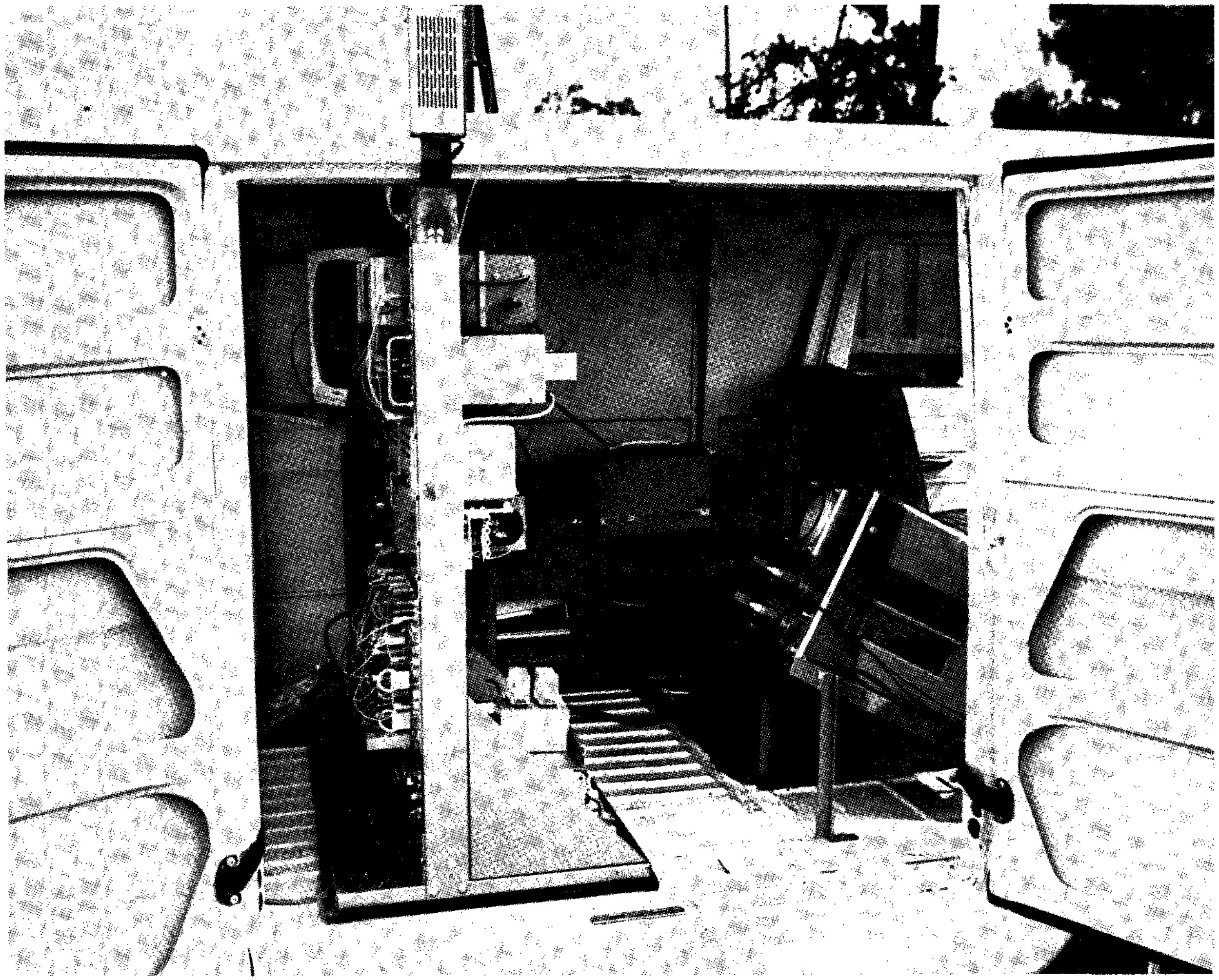


Fig. 21 CONTROL STATION - SIDE VIEW CLOSE UP

Fig. 22 VEHICLE ON TEST PATTERN APPROACH

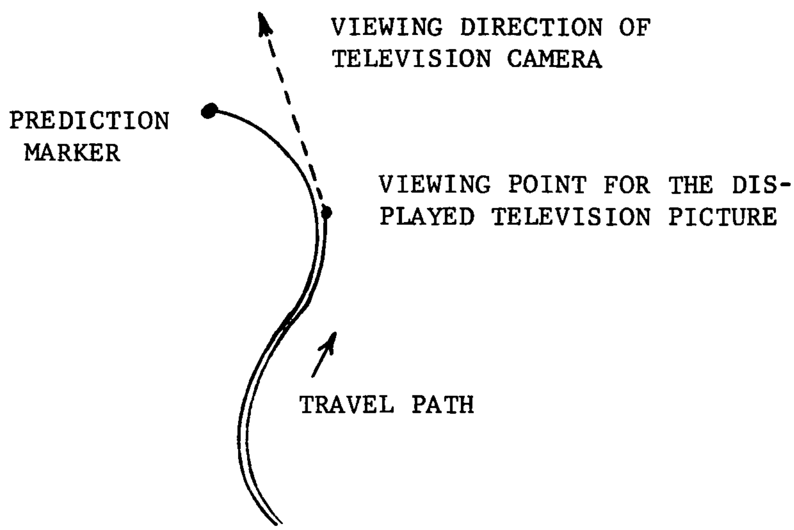


Fig. 23 PLAN VIEW OF THE PREDICTION MARKER

vehicle is shown at the starting point of a tangent that is used as an approach to the test course in tracking experiments.

D. COMPUTER CALCULATIONS

Fig. 23 is a plan view showing the situation that exists between the view of the landscape as seen on the television monitor and the prediction marker. We can imagine two objects travelling across a map with the second following the first by an amount equal to the total signal transmission lag present in the control system. The second object represents the viewing point on the path of travel for the television picture displayed at the control station, while the first object represents the prediction marker. We are interested in the amount by which the marker leads the viewing point for the displayed television picture. In particular, it is important to know the marker position with respect to the viewing direction of the television camera. In reality, the television camera on the vehicle shows only a view of the landscape. It is up to the prediction computer to determine the correct location for superimposing the marker on the television display.

Two operating conditions must be considered. The first involves the starting conditions of a run. During the first delay period, equal to the total signal transmission lag, the operator observes a stationary television view of the landscape. Although the operator may be sending out steering instructions, the television picture will not show the effects of vehicle motion until the first delay period has elapsed. During the starting condition, the prediction marker responds immediately to all commands and drives out across the stationary view of the landscape.

After the first delay period has passed, the television picture shows the effects of the motion of the vehicle. The landscape approaches the observer watching the television display. The marker no longer moves out across the picture but continues to move over the landscape a fixed distance in front of the viewing point of the television picture. The calculations needed to locate the marker are more involved, since they must consider the motion of the viewing point of the displayed television picture as well as the output steering commands. The situation that exists after the television picture shows the effects of vehicle movement is the second operating condition.

The test vehicle itself steers by changing its direction of travel in a series of 1.8° turns. The path traced over the surface of the landscape is approximated by a series of straight line segments.

The computer used is a real-time computer in the sense that it carries out the computer maneuvers at the same rate that the vehicle carries out its maneuvers. The predictor is developed by calculations representing "growth" on the advanced end of the prediction segment, with a means for "decay" at the other end. Only the marker at the advanced end of the prediction line segment is displayed.

To avoid cumulative error, separate "growth" and "decay" calculations are not made. Instead, only a single master set of calculations is made. The master set of calculations is used to represent the progress of both the prediction marker and the viewing point for the displayed television picture. This master set of calculations is developed in immediate response to all steering commands. The information describing this set of calculations is delayed for one delay period by using the tape recorder, already present in the control station, for delaying steering instructions being sent to the vehicle. The two sets of calculations are subtracted continuously, and a transformation of coordinates is performed on the results to properly orient the prediction marker with respect to the viewing direction of the television display.

This procedure offers the advantage of no cumulative error since any calculative errors made reappear one delay period later in the delayed calculations and are subtracted from the running total. The master set of calculations is always referenced back to the origin of the experimental run, so that the integrators that accumulate X and Y totals may saturate; a means for periodically re-setting these integrators without upsetting the end result is explained later.

Since computer information must be stored on a tape recorder, the FM Datacoder is necessary to convert DC voltage levels representing X and Y values to variable frequency signals that can be recorded on tape. The FM Datacoder also provides the recovery of DC levels from the variable frequencies that are reproduced from the tape.

Fig. 24 shows the various stages used in the determination of the prediction marker position. Because each steering pulse causes a single step of 1.8° to the right or left,

$$\alpha_i = \alpha_{i-1} \pm 1.8^{\circ}$$

Each of the straight line segments, representing the progress of the vehicle, accumulates smoothly in the integrators. For convenience of observation, however, Fig. 24 shows the calculations developing in a discrete series of steps rather than in the smooth manner actually used. For a typical segment:

$$\delta x_i = V_R \Delta t_i \cos \sum \alpha_i \qquad \delta y_i = V_R \Delta t_i \sin \sum \alpha_i$$

where V_R is the reference speed of growth, $\sum \alpha_i$ is the accumulated direction of travel, and Δt_i is the time length of the segment. The location of the end point (x,y) is expressed by summing all the elements to get:

$$X = V_R \sum_{i=1}^{N} \Delta t_i \cos \sum \alpha_i \qquad Y = V_R \sum_{i=1}^{N} \Delta t_i \sin \sum \alpha_i$$

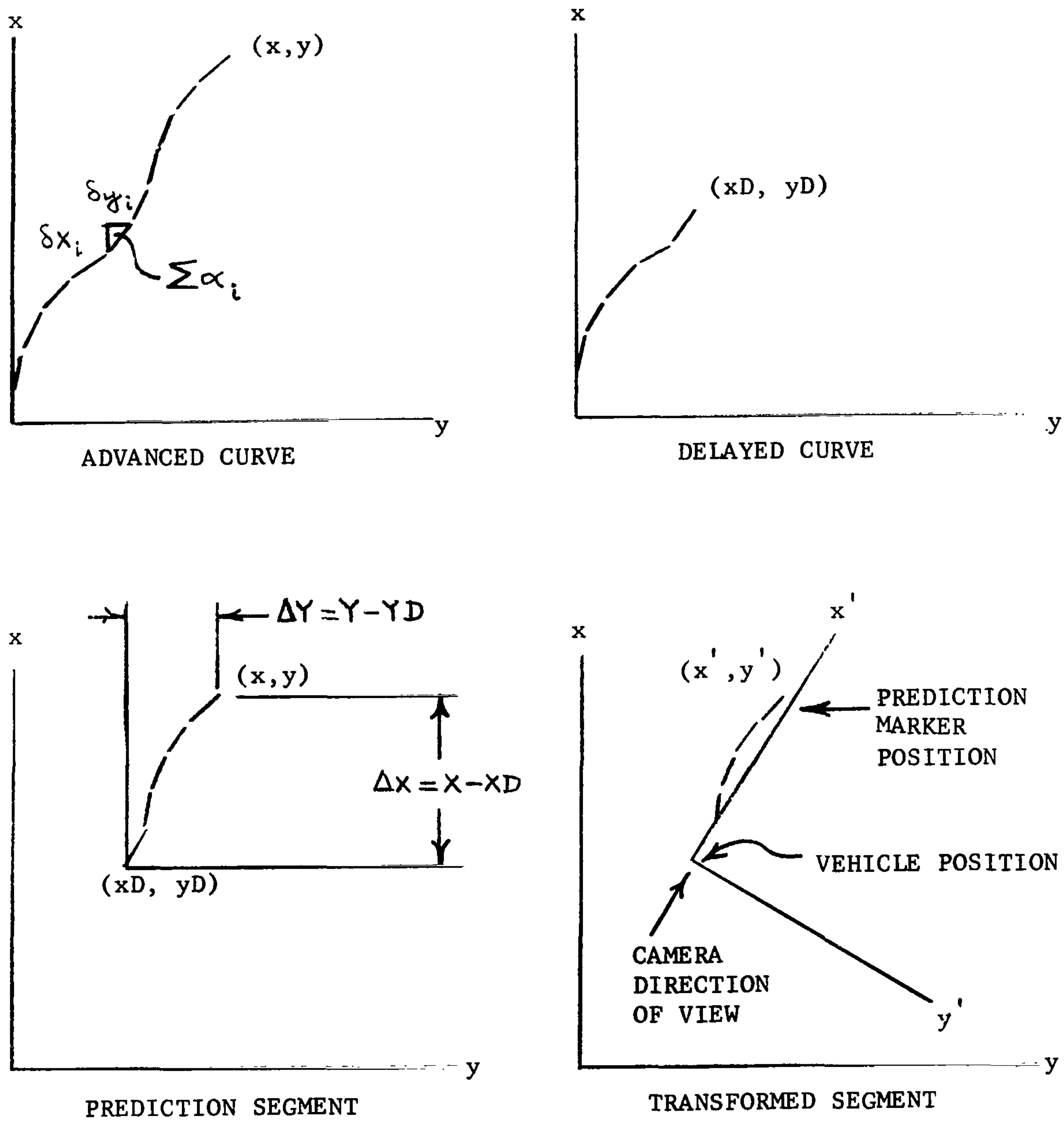


Fig. 24 REAL-TIME COMPUTER II CALCULATIONS

Since all segments develop through the integrators in the computer, the end point is expressed as:

$$X = V_R \sum_{i=1}^{N} \int_{t_i}^{t_{i+1}} \cos \sum \alpha_i \, d\tilde{J} \qquad Y = V_R \sum_{i=1}^{N} \int_{t_i}^{t_{i+1}} \sin \sum \alpha_i \, d\tilde{J}$$

The x and y values are stored on tape to reappear as:

$$XD = V_R \sum_{i=1}^{d} \int_{t_i}^{t_{i+1}} \cos \sum \alpha_i \, d\tilde{J} \qquad YD = V_R \sum_{i=1}^{d} \int_{t_i}^{t_{i+1}} \sin \sum \alpha_i \, d\tilde{J}$$

where $d < n$.
The prediction segment is then represented by the difference as:

$$\Delta X = X - XD \qquad \Delta Y = Y - YD$$

Finally, the transformation of coordinates is achieved by using:

$$X' = \Delta X \cos \sum \alpha_d + \Delta Y \sin \sum \alpha_d$$

$$Y' = \Delta Y \cos \sum \alpha_d - \Delta X \sin \sum \alpha_d$$

The computer carries out the above calculations made separately and in the sequence shown.

E. PREDICTOR CHARACTERISTICS

The details of the control station are shown in Fig. 25. The details of both the steering loop and the predictor are shown with the single exception of the television monitor and the computer television camera are not included.

The reset device serves an important function. Since vehicle travel distances may accumulate without limit from the origin of a test, the integrators representing these distance components by DC voltage levels may also increase without limit. The operational amplifiers saturate at a level of 100 volts. The reset device is used to prevent saturation. When an integrator output reaches ± 80 volts, a reset switch operates to short the integrator capacitor through the relay points. This results in an almost immediate reset of the integrators to zero. A sudden change of 80 volts in one of the integrators causes a sudden 80 volt change in the output of the ΔX or ΔY summer. The summer output should not experience a shift due to the reset operation. Therefore, when an integrator output suddenly resets, a correction flip-flop operates in response to the derivative of the integrator output. When this flip-flop operates, it energizes a high speed relay through which the correction voltage of 80 volts is sent to the summer. Within one millisecond of a reset operation, an

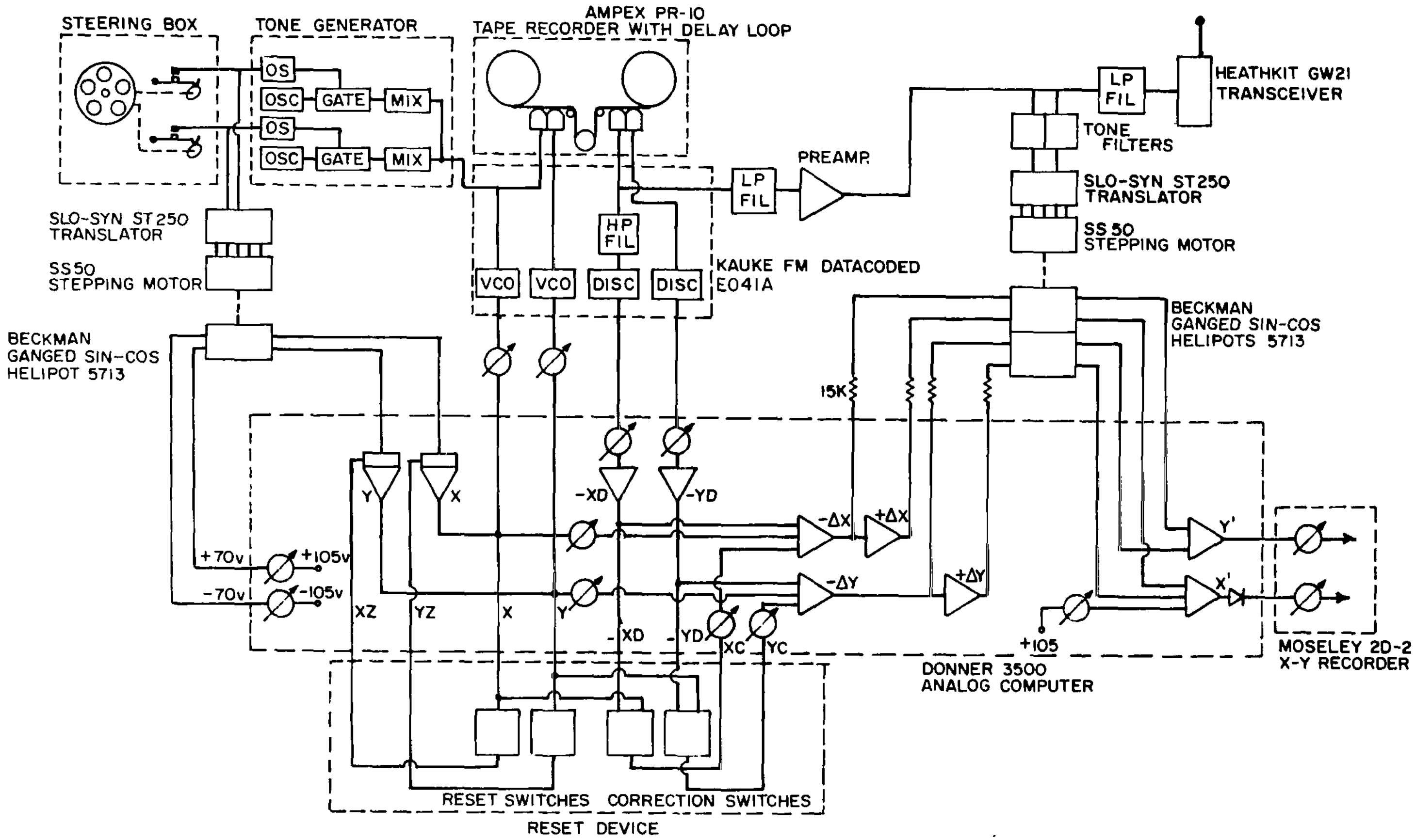


Fig 25 CONTROL STATION WIRING DIAGRAM

80 volt correction is applied to hold the summation value constant. The sudden discontinuity in the integrator output appears from the tape recorder one delay period later. At this time the 80 volt jump is subtracted. The release of the correction switch flip-flop is all that is needed to preserve the value at the summer. No cumulative error can remain from a reset operation. Since a correction flip-flop operates at both ends of a reset delay period, only one correction can be processed during a given delay period. The choice of referencing the sine-cosine potentiometers with a ± 70 volts permits the use of amplifiers near capacity without requiring more than one reset in a given delay period. The calculations are such that none of the operational amplifiers, with the exception of the two integrators, ever approach saturation.

Detail drawings of the computer electronics appear in Appendix B of this paper.

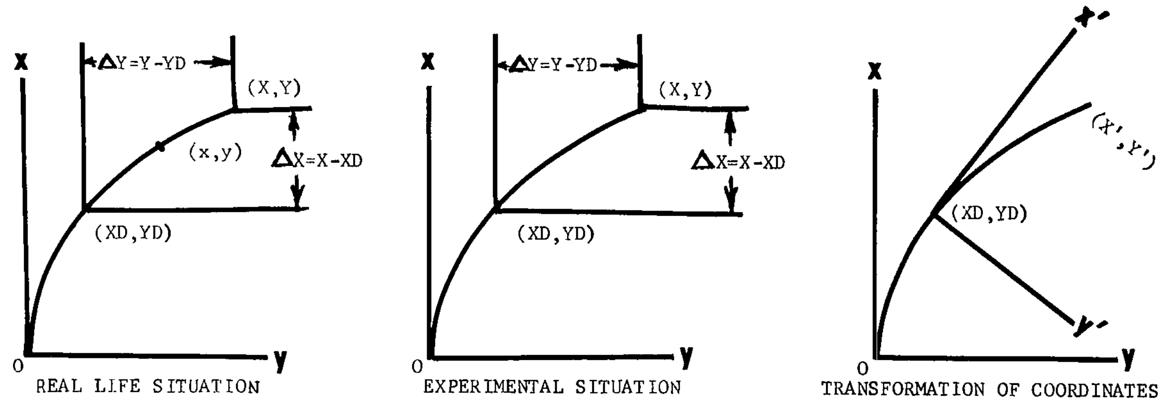
F. LUMPED TIME DELAYS

The statement has been made that for convenience the signal transmission lag is equally divided in the feed forward radio link and the feedback television link in a real mission, but is lumped in the feed forward radio link for the experimental arrangement. This eliminates the need for a video tape delay unit. Also, throughout this discussion, the use of a tape recorder to simulate the entire or lumped signal transmission lag is shown and described. It is appropriate at this point to examine the validity of the contention that, as far as the human operator is concerned, the two situations of distributed and lumped delays are equivalent.

Newman (11) delivered a paper to the Lunar Missions Meeting in Cleveland, Ohio in July, 1962, in which he discussed the problems of remote control of lunar vehicles from earth. In reviewing the experimental work that had been done up to that point, he noted that the use of a lumped signal transmission lag instead of an even division between the outgoing and the returning links that would occur real missions.

Newman raised the important question as to whether the lumped delay arrangement used in experimental studies adequately simulates the control problem for a real mission. Fig. 26 illustrates that the two situations are similar from the driver's point of view. The vehicle obviously has a different location between the point of origin of the displayed picture and the predicted position, but this is something the driver can not recognize. In both cases the driver must control through a feedback delay totaling 2.6 seconds. Prediction markers lead the video picture of the landscape by the same amount in both situations. A comparison of the situations is made in Fig. 26.

In a real mission, a 2.6 second delay unit will be needed for



1. THE X,Y COORDINATE SYSTEM IS LOCATED AT THE POINT WHERE A RUN BEGINS. THE X AXIS POINTS IN THE DIRECTION IN WHICH THE VEHICLE WAS HEADED AT POINT O.

2. AS THE VEHICLE TRAVELS ALONG THE PATH ITS TV CAMERA REPORTS PROGRESS BY VIEWING THE CHANGING LANDSCAPE AT A RATE OF 30 FRAMES PER SECOND. THIS CHANGING VIEW OF THE LANDSCAPE APPEARS ON A TV MONITOR AT THE CONTROL STATION.

3. DUE TO TRANSMISSION TIME DELAYS, THE VIEW OF THE LANDSCAPE TAKEN AT POINT (XD,YD) DOES NOT REACH THE CONTROL STATION MONITOR UNTIL THE VEHICLE ADVANCES TO POINT (x,y). THE VEHICLE WILL CONTINUE TO POINT (X,Y) AS IT FOLLOWS THE REMAINING INSTRUCTIONS CURRENTLY EN ROUTE BY RADIO LINK.

4. IN THE EXPERIMENTAL SITUATION, THE ROUND TRIP TRANSMISSION DELAY BETWEEN THE CONTROL STATION AND VEHICLE IS LUMPED IN THE CONTROL STATION TO VEHICLE LINK. AS A RESULT THE VIEW OF THE LANDSCAPE TAKEN AT POINT (XD,YD) REACHES THE CONTROL STATION MONITOR IMMEDIATELY. DUE TO THE ARTIFICIAL DELAY BUILT INTO THE EXPERIMENTAL EQUIPMENT, THE VEHICLE WILL CONTINUE ON TO (X,Y) AS IT FOLLOWS ALL INSTRUCTIONS CURRENTLY BEING PROCESSED.

5. IN BOTH CASES POINT (X,Y) IS A PREDICTION OF WHERE THE VEHICLE SHOULD GO WITH RESPECT TO THE LANDSCAPE AS VIEWED FROM POINT (XD,YD) IF IT CORRECTLY OBEYS ALL DRIVING INSTRUCTIONS FOR TRAVEL BEYOND (XD,YD).

6. IN BOTH CASES X AND Y REPRESENT THE COORDINATE AMOUNTS BY WHICH (X,Y) LEADS (XD,YD).

7. THE X',Y' AXES MOVE ALONG THE PATH WITH POINT (XD,YD). THE X' AXIS IS TANGENT TO THE PATH AT (XD,YD) IN THE DIRECTION IN WHICH THE VEHICLE'S TV CAMERA VIEWS THE LANDSCAPE.

8. THE POINT (X',Y') REPRESENTS THE AMOUNT BY WHICH THE PREDICTED SPOT LEADS (XD,YD) PROPERLY ORIENTED WITH THE VEHICLE'S VIEW OF THE LANDSCAPE.

Fig 26 PREDICTION COORDINATES

the prediction calculations. In the experimental arrangement with lumped time delays, a single delay unit is sufficient to handle the 2.6 second total signal transmission lag and the 2.6 second delay needed for the predictor calculations. However, if signal transmission lags were distributed in the experimental arrangement, three delay units would be needed. A 1.3 second delay unit would be required to simulate the radio signal transmission lag, a 1.3 second video delay unit would be needed to simulate the television transmission lag, and a 2.6 second delay unit would be needed for the predictor calculations. The use of the lumped time delays in the experimental arrangement not only avoids the need for a video delay unit, but also avoids the need for a separate delay unit for the predictor calculations. The single tape delay unit automatically adjusts the predictor delay length to agree exactly with the total signal transmission lag.

G. HUMAN USE OF THE PREDICTOR

Now that the details of the predictor are complete, it is important to examine the use of the equipment from the human point of view, and to consider the way in which the prediction marker moves on the television display.

When a turn is introduced, the motion of the prediction marker is somewhat different than the apparent motion of a similarly advanced point for the case where there is no signal transmission lag. The difference depends on whether the television camera turns or whether the prediction marker turns. When the camera turns, advanced points on the landscape swing through an arc. When the prediction marker turns, however, it does not swing across the television screen, but merely changes the direction in which it appears to slide over the landscape. In other words, the motion of the marker is not as pronounced as an observer might expect from the experience he has with automobiles. Time is required before it is perfectly clear that the direction of the marker travel has not changed. It may be important to add a vector to the marker to indicate the direction of travel. On the other hand, the operator has kinesthetic feedback from turning the steering wheel, emphasizing that the marker is changing direction.

H. PREDICTOR MOTIONS ON TV DISPLAY

Another factor should be considered in the action of the marker moving over the terrain. This is perhaps best shown by considering the effects of a unit turn to the right. Before the turn, the marker is located straight ahead, and appears along the vertical center line of the television camera. As the vehicle continues ahead, the marker leads straight ahead and appears to slide over the ground. When the turn is introduced, the marker changes direction and begins to slide over the terrain a few degrees to the right in immediate response to the command. The vehicle, of course, continues straight ahead since it will not respond to the turn command until one delay period of 2.6 seconds has elapsed. As the delay period continues, the marker slides further to the right, showing how the predicted travel is moving away from the direction in which the vehicle moves prior to its turn. Finally, the vehicle turns, and almost immediately the television picture swings around to the new direction. The vehicle has finally responded to the instructed turn and is now looking directly up the predicted road towards the marker. Having chased the marker around the corner, the vehicle television camera sees the marker position straight ahead once again, and all prediction reference to the turn has vanished. To summarize, each turn consists of a 2.6 seconds drift of the marker towards the side of the screen, followed by a rapid reset to center as the vehicle finally makes the turn. During the drift, the marker slides across the scenery. During reset, both the marker and the landscape swing across the screen as the television camera on the vehicle describes the turn. The important point for the operator is not to watch the motion of the marker on the monitor, but to concentrate on the motion of the marker with respect to the landscape.

A large change of direction is made up of a series of such incremental turns. In a complex maneuvering situation, many turns may be in the process of being passed through the time delay at once. The net result is an involved behavior of the marker as it slides over the ground in response to new commands and resets with the view of the landscape as the vehicle follows the previously commanded turns.

I. PREDICTOR CALIBRATION

The operator may wish to confirm the accuracy of the predictor when in use. Several tests can be applied. One is to drive straight for at least one delay period at which time the marker should return to a central position one delay period's worth of travel in front. By noting the marker's position, the driver will know if the predictor has developed an error. A second operator could then make any necessary adjustments while the control system is still in use. Another test procedure is for a second operator to identify a particular landmark that happens to coincide momentarily with the marker. By watching to see if the landmark approaches the observer correctly along the centerline of the television monitor display or if it drifts to one side, he will know if the predictor has become biased. By measuring the time required for the landmark to approach the observer, he will know if the prediction is being made long or short of the proper distance. Both types of errors could be corrected by suitable computer adjustments while the vehicle is running. Finally, the operator can always stop periodically, reset the predictor equipment, and start over again with a clean computer.

CHAPTER III

EXPERIMENTAL EVALUATION AND CONCLUSIONS

A. DISCUSSION OF FIELD TESTS

Following the development of the control system, a series of field tests was conducted. In this work, we used the lunar delay period of 2.6 seconds. The vehicle speed was measured at 7.1 feet per second, which is close to the intended 7.35 feet per second (5mph). The selected speed is well beyond the speed where effective unaided control is lost (1),(3). The ability to drive at 7.1 feet per second with the help of the predictor represents a large step forward. The vehicle was operated at constant speed over flat terrain, and the television camera on the vehicle used the standard frame rate of 30 frames per second.

The first experiments involved tracking a white line that was drawn on the surface of the test field. Tracking permits a ready means for scoring and for evaluating driving ability. In a real mission, we will not find white lines to follow. Nevertheless, a tracking problem remains. After looking ahead to select an intended path of travel, the operator can proceed to track along the terrain features that identify the route. The situation is more difficult because path determination is added to the tracking operation. In a real mission, the driver does not have to return to a particular route of travel if he strays from the intended path; he can develop an alternate route to follow.

The second group of experiments was designed to give the operators this added freedom. A test course was established to simulate the case of an open field with a series of obstacles that the vehicle must pass between. This arrangement is analogous to a croquet court with open spaces between a series of wickets. The drivers had to steer the test vehicle through these wickets in sequence, but the drivers were perfectly free to select their routes of travel in the open areas between the wickets. This course is identified as a maze throughout the present chapter.

The shape of the tracking curve was determined by a consideration of vehicle maneuverability, the viewing angle of the vehicle's television camera, and the size of the available test field. The curve developed is a compromise between requiring involved maneuvers and keeping the curve in view at least one prediction length ahead of the picture. At no time is the driver asked to steer the prediction marker off of the television display of the scenery. The curve itself is basically an oval which is distorted to take advantage of the shape of the field. Six sine waves of various amplitudes and lengths are superimposed on the oval.

B. DRIVER TRAINING

Driver training was conducted in a sequence identical to the order in which the experimental data was collected. In the opening phases of the program, the drivers were asked to follow the white line when there was no delay in the system. This gave them the opportunity to become familiar with steering a highly-responsive four-wheel steering vehicle. They gained the ability to drive by observing a television picture of the course. After achieving this familiarity with the equipment, the drivers practiced tracking without a predictor and with delay periods of 1.3, 2.6, 3.9, and 5.2 seconds. This experience gave them an appreciation for the difficulty encountered when signal transmission lags are introduced into a control system. The final training period for tracking involved practice using the predictor.

During the practice session with the predictor tracking, the drivers gained confidence in the ability of the predictor to indicate the test vehicle's future behavior correctly. This confidence was reinforced by watching the way in which the white line approached the television camera on the vehicle in response to steering instructions. After this experience with being able to see a precise feedback of success by watching the approach of the white line, the drivers shifted to practice with the maze.

The decision was made to record the experimental runs on movie film so that we would have a permanent record of each performance. This enabled us to go back over each run in order to examine and measure performance. A movie film record makes larger demands on manpower and equipment. For this reason we established the policy of recording experimental data on film after the drivers had a thorough training period in which they developed their skills at driving under various experimental conditions. The results presented in this paper show how well the drivers were able to master the different experimental conditions.

During the training period, several interesting things appeared. It was discovered that the drivers learned rapidly to track without a delay. A longer period was required to gain familiarity with the predictor. By far the longest training period, however, was required in trying to gain control when no predictor was used and signal transmission lags were present.

Another significant discovery was that the ability to drive without a predictor improved once the drivers learned to use the predictor. Apparently the predictor experience showed the drivers the area on the television display where their mental calculations should locate an imaginary prediction marker. As one driver exclaimed, "So that's where it's supposed to be!" Perhaps even more important is the fact that the predictor experience showed them the way in which the prediction marker moves about on the television display in responding to steering instructions. As discussed in Chapter II, the motion of the prediction marker on the television display is influenced by the immediate response of the marker to the steering commands, and it is also influenced by the eventual response of the robot vehicle to the same commands.

C. TRACKING EXPERIMENT

1. TEST PROCEDURE

One way to score a field tracking experiment is by a time-on-target record. This was used by Adams (1) in his vehicle studies. Grumman (7) used a similar scheme by counting the number of collisions with the traffic cones used to outline test "roads." As a start in data collecting for the present work, the time-on-target approach was used. The target was arbitrarily selected as the vehicle width, and percentage time for keeping this target over the line was recorded for each driver. This approach did not yield sufficient information in our experiments, so we decided to make a photographic record of each experimental run.

A photographic record was obtained by taking 16 millimeter movie pictures from the top of a 50 foot tower in the center of the field. The camera was equipped with a telephoto lens so that the vehicle and its immediate surroundings could be seen clearly.

To recreate the behavior of the vehicle during the experimental runs, a rectangular coordinate system was marked out on the field. It was felt, however, that the drivers might use the grid lines for guidance in tracking if the grid lines appeared in the television pictures seen at the control station. For this reason a complete gridwork was not drawn across the field, and only the intersection points were marked. These crosses were not apparent to the test drivers, but were clearly seen by the movie camera looking down from the recording tower.

After the experimental runs were recorded on movie film, it was necessary to examine the films frame by frame so that runs could be reconstructed on paper. This was done on a scale where 15 feet on the field was reduced to one inch on the drawings. Both the white line being tracked and the actual performance of the vehicle were reproduced for each experimental run. Finally, the large drawings were photographically reduced for inclusion in this paper.

This may seem like an elaborate way to obtain data, but it permits a detailed view of each tracking performance. Each performance can be examined as a whole. System instabilities can be observed, and the way in which control is recovered following errors can be seen. The places where instabilities are excited is apparent.

Numerical conclusions can be obtained from these performance patterns. Root mean square values of tracking error can be determined to characterize each run by a single number. Undue emphasis, however, should not be placed on a single identifying number. Entirely different tracking performances may have the same RMS number. RMS values should only be used in conjunction with observations of the performance patterns. In this way, they are helpful in establishing relative performance levels. In determining RMS values, tracking errors were measured at one inch spacing along the reproduction of the white line on the large drawings. This was done before the drawings were photographically reduced for this paper.

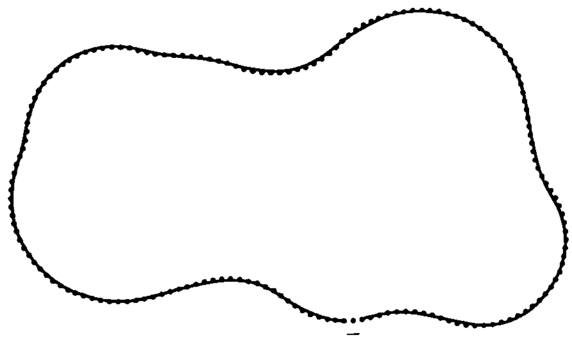
The values of tracking error taken at these measurement stations are shown in the frequency distribution illustrations. These illustrations permit a rapid visualization of the tracking accuracy. By noticing the way in which the frequency distribution graphs are either spread out over a wide range or are clcsely bunched about a mean value, a comparative evaluation of the runs can be made. Since the mean values for all the recorded runs are nearly zero, displacements are measured from the white line being followed.

Another advantage in having a complete photographic record of tracking behavior is that useful time-on-target data can be obtained. One of the major difficulties in scoring by time-on-target means is in choosing the target size. This leaves one in the uncomfortable position of having to defend the target size selected. What is the logical target size? How much leeway is permitted before a track is considered unacceptable? What target width can be selected so that the experimental results will be of general interest for cases using different vehicles, and for cases where different driving accuracies are required? By using the information available from a complete tracing of driving performances, graphs can be obtained showing plots of percentage time-on-target versus target size. This provides a self-service arrangment where the reader may select the target size best suited for his particular needs.

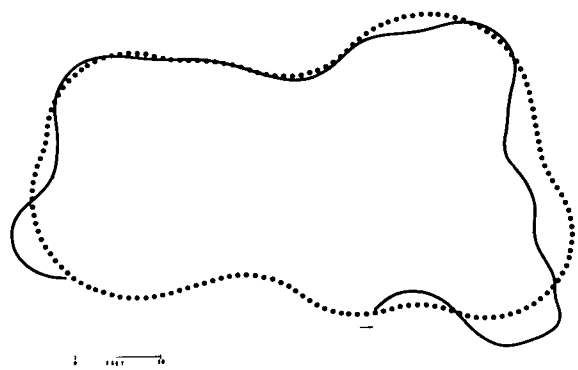
The percentage time-on-target can be obtained for a given target size. Conversely, if a minimum time-on-target performance record is specified, the minimum acceptable target size can be found. This makes it possible to find the minimum spacing between obstacles that can be considered in selecting a direction of travel. If no errors are permitted, the minimum target width for 100% time-on-target can be used in establishing the minimum sized "road" that the vehicle can follow without difficulty.

2. TRACKING DATA

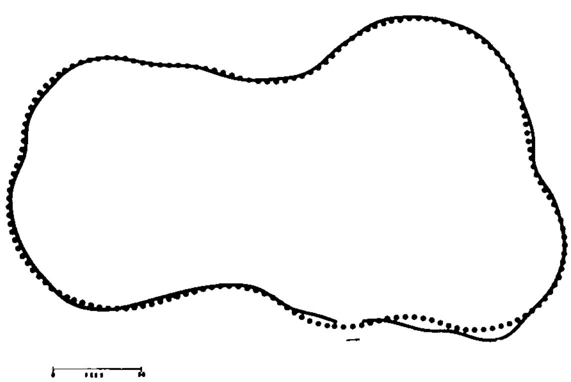
Figs. A1 through A11 show the tracking abilities of rwo operators who are identified as Driver A and Driver B. The RMS error values for these runs are tabulated below. Where duplicate runs were made, the combined RMS values are also given. Three typical curves are included in this section, in Fig. 27, to show a comparison of no delay and delay driving with and without a predictor.



(a) WITHOUT DELAY



(b) 2.6 SEC. DELAY - WITHOUT PREDICTOR



(c) 2.6 SEC. DELAY - WITH PREDICTOR

Fig. 27 COMPARISON OF TRACKING PERFORMANCES

FIGURE	DRIVER	SIGNAL TRANS. LAG.	WITH PRED.	RMS ERROR	COMBINED RMS ERROR
A1	A	0 sec.	no	0.75 ft.	0.76 ft.
A2	A	0	no	0.77	
A3	A	2.6	no	9.75	7.67
A4	A	2.6	no	5.59	
A5	A	2.6	yes	2.03	1.72
A6	A	2.6	yes	1.40	
A7	B	0	no	0.42	0.64
A8	B	0	no	0.86	
A9	B	2.6	no	6.61	6.61
A10	B	2.6	yes	2.64	2.85
A11	B	2.6	yes	3.06	

TABLE 1 TABULATED TRACKING DATA

The runs where a signal transmission lag is inserted but where the predictor is not used show a great deal of instability. Fig. 27b shows a violent oscillation near the beginning of the run, a period where the disturbance dies out, and a final portion where oscillations are excited once again. The photographic record terminated before the run was completed, so the curve does not show the consequences of the final oscillations. The other two unaided but delayed runs also show instabilities and positions where the oscillations are temporarily damped. Some numerical spread appears in the RMS values and reflects the erratic behavior of driving without a predictor when time delays are present.

The predictor runs also show that Driver A is better able to track with a predictor than Driver B. In fact, Driver A's predictor RMS error values are close to the case of a three foot vehicle which is just able to straddle the line. It is expected that performance varies between individuals. Presumably, with a more rigorous selection process. we could discover drivers with an even better performance ability. The results of Driver A establish a lower bound of performance for this man-machine system. An examination of Fig. 27c also shows that the run started with an error that was damped out rapidly. The RMS value for this run was largely due to this error.

Figs. 28 and 29 are frequency distribution records of Driver A and Driver B's tracking abilities. The frequency distribution information represents the errors measured at the evenly-spaced stations along the white line. The results show how accurately the performance without centers on the white line. The three center-most bars combine to show the ability to straddle the white line with our three foot wide vehicle.

Table 2 and Figs. 30 and 31 show the percentage time-on-target for targets of various widths.

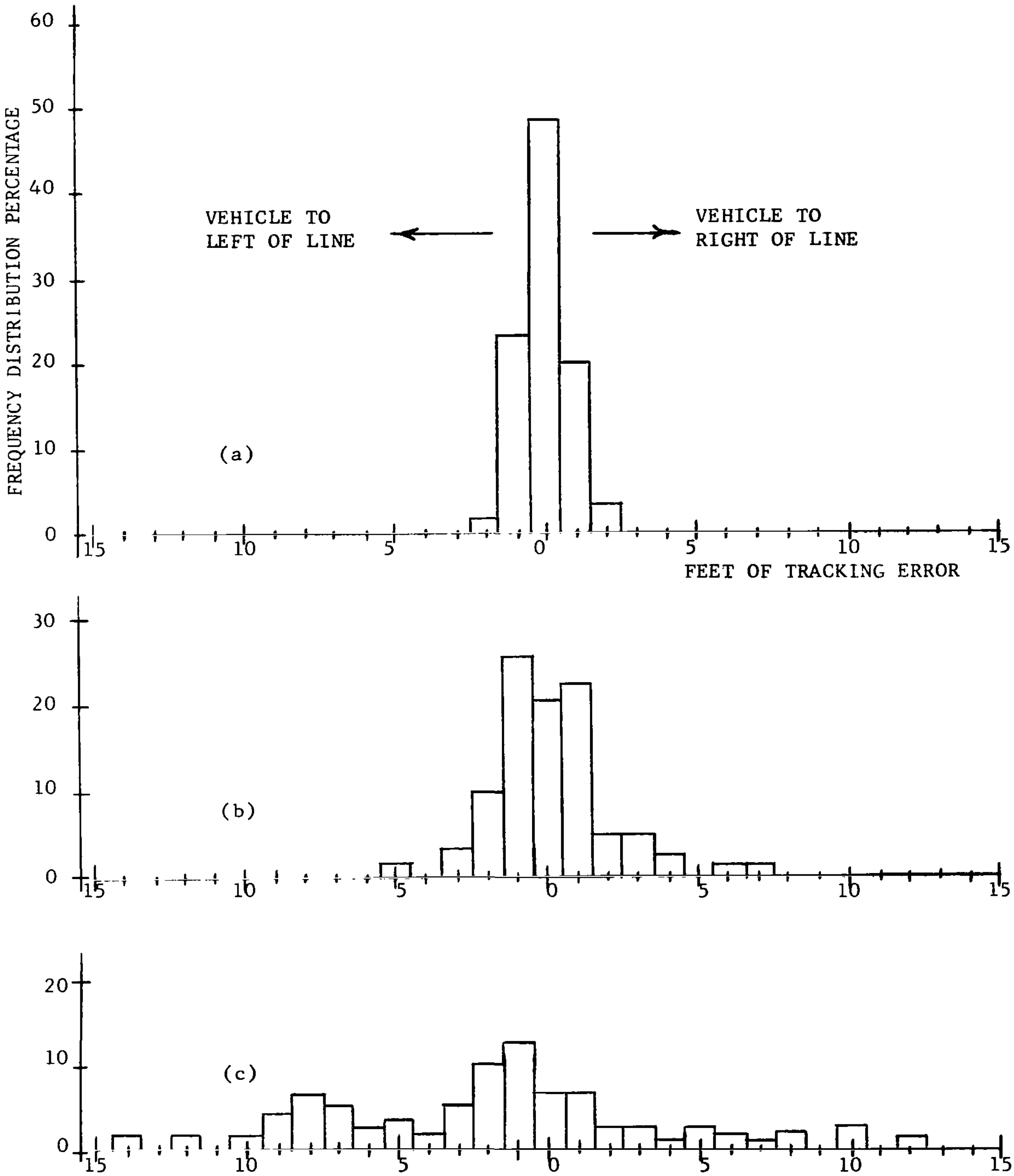


Fig. 28 TRACKING ERROR FREQUENCY DISTRIBUTION - DRIVER A
(a) with no signal transmission lag
(b) with 2.6 seconds signal transmission lag and with predictor
(c) with 2.6 seconds signal transmission lag and without predictor

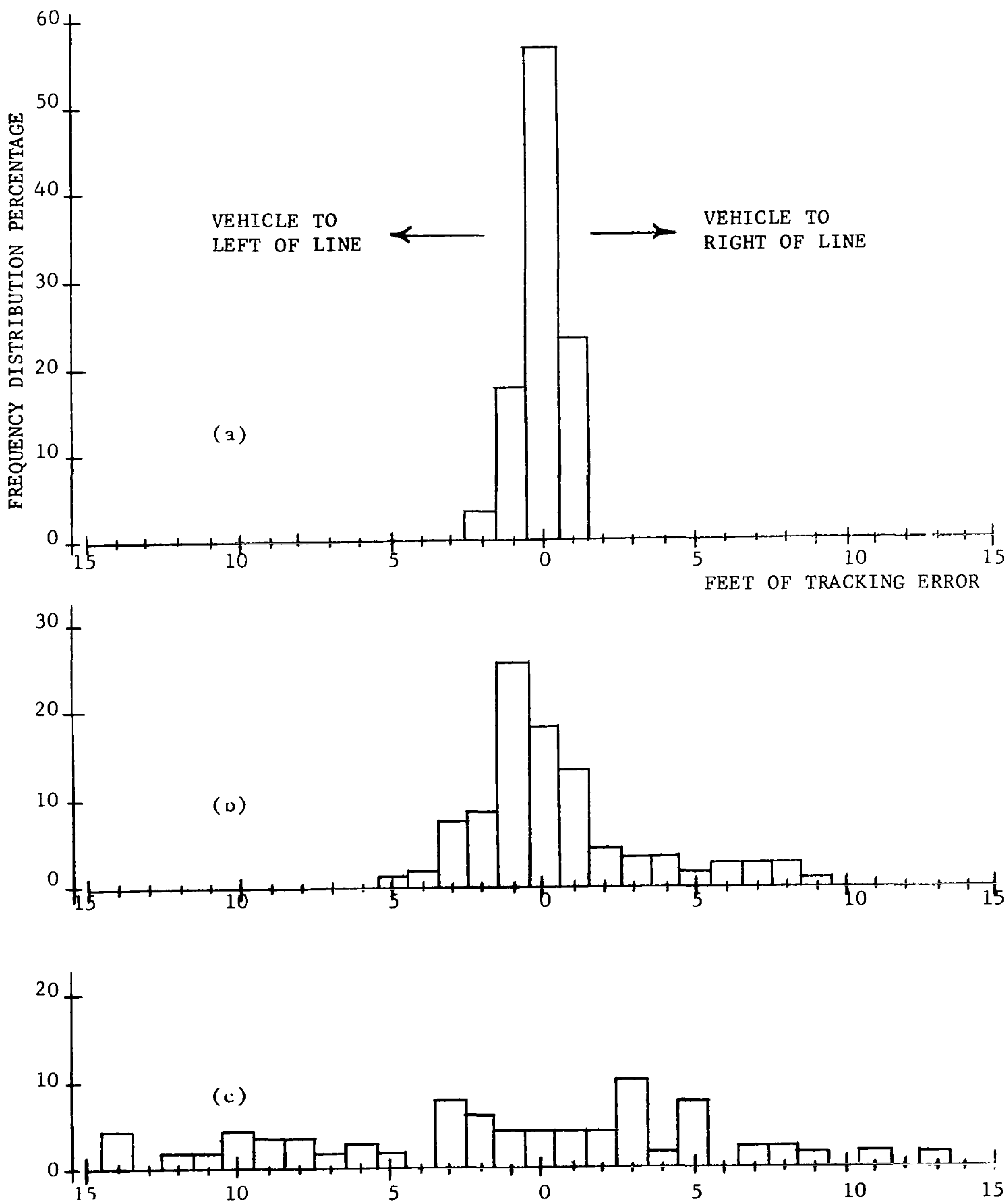


Fig. 29 TRACKING ERROR FREQUENCY DISTRIBUTION - DRIVER B
(a) with no signal transmission lag
(b) with 2.6 seconds signal transmission lag and with predictor
(c) with 2.6 seconds signal transmission lag and without predictor

TARGET DIAMETER		DRIVER A			DRIVER B		
D FEET	$\frac{D}{vT}$	NO DELAY	DELAY NO. PRED.	WITH PRED.	NO DELAY	DELAY NO. PRED.	WITH PRED.
1 ft.	0.05	49.5%	7.0%	21.2%	56.6%	5.3%	18.7%
3	0.16	96.7	27.0	69.8	96.4	15.9	58.9
5	0.27	100.0	40.0	85.5	100.0	28.1	72.0
7	0.38	100.0	48.0	94.5	100.0	49.2	83.2
9	0.49	100.0	51.0	97.1	100.0	52.8	88.8
11	0.60	100.0	58.0	98.2	100.0	65.1	90.6
13	0.74	100.0	63.0	99.2	100.0	70.4	93.4
15	0.81	100.0	69.0	100.0	100.0	77.4	96.2
17	0.92	100.0	78.0	100.0	100.0	82.7	99.0
19	1.07	100.0	82.0	100.0	100.0	89.8	100.0
21	1.16	100.0	87.0	100.0	100.0	93.4	100.0
23	1.28	100.0	87.0	100.0	100.0	95.2	100.0
25	1.35	100.0	90.0	100.0	100.0	100.0	100.0
27	1.45	100.0	90.0	100.0	100.0	100.0	100.0
29	1.56	100.0	92.0	100.0	100.0	100.0	100.0
31	1.67	100.0	94.0	100.0	100.0	100.0	100.0
33	1.78	100.0	94.0	100.0	100.0	100.0	100.0
35	1.89	100.0	96.0	100.0	100.0	100.0	100.0
37	1.98	100.0	98.0	100.0	100.0	100.0	100.0
39	2.10	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 2 TIME-ON-TARGET VERSUS TARGET SIZE

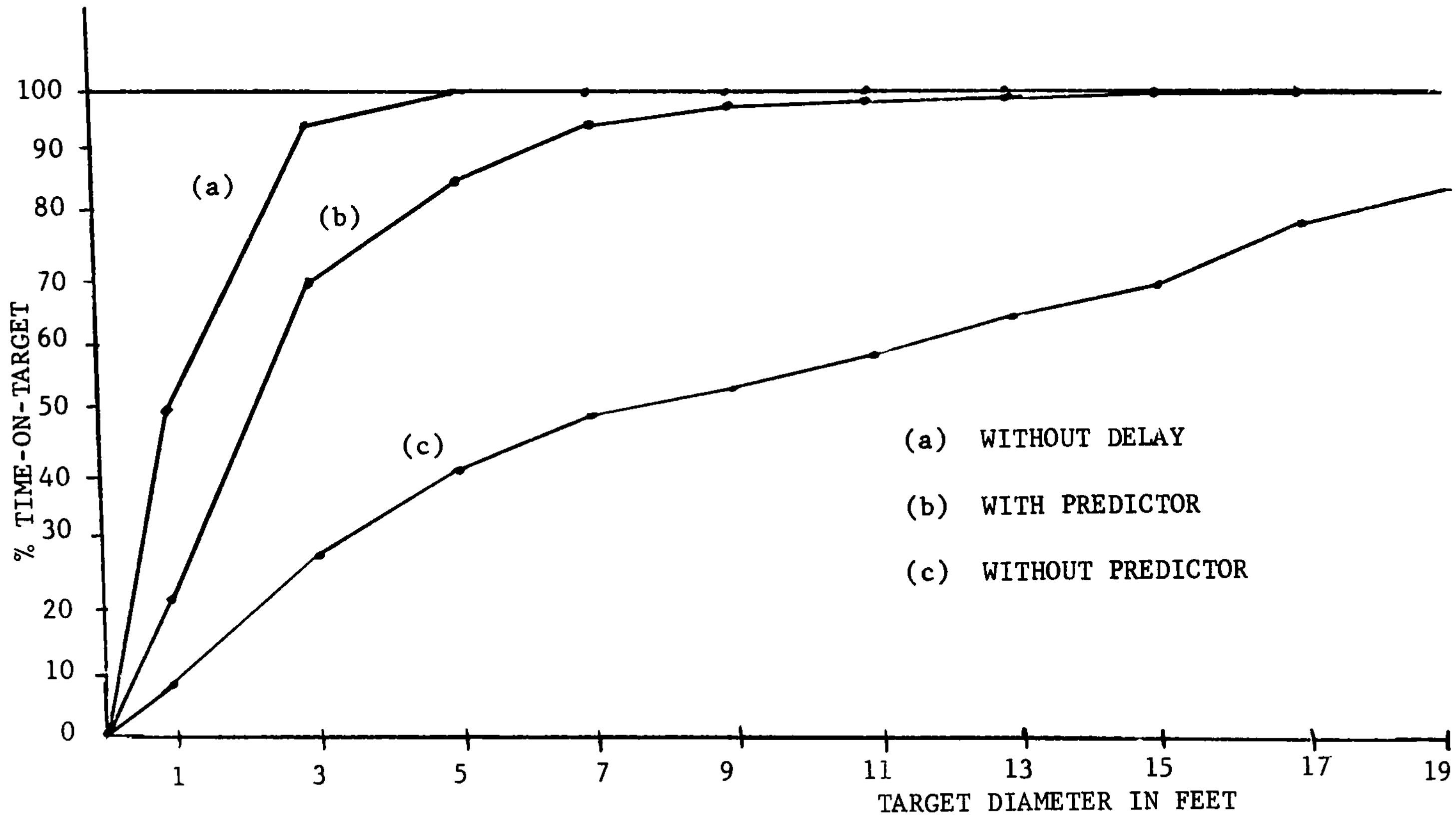


Fig. 30 TRACKING - DRIVER A

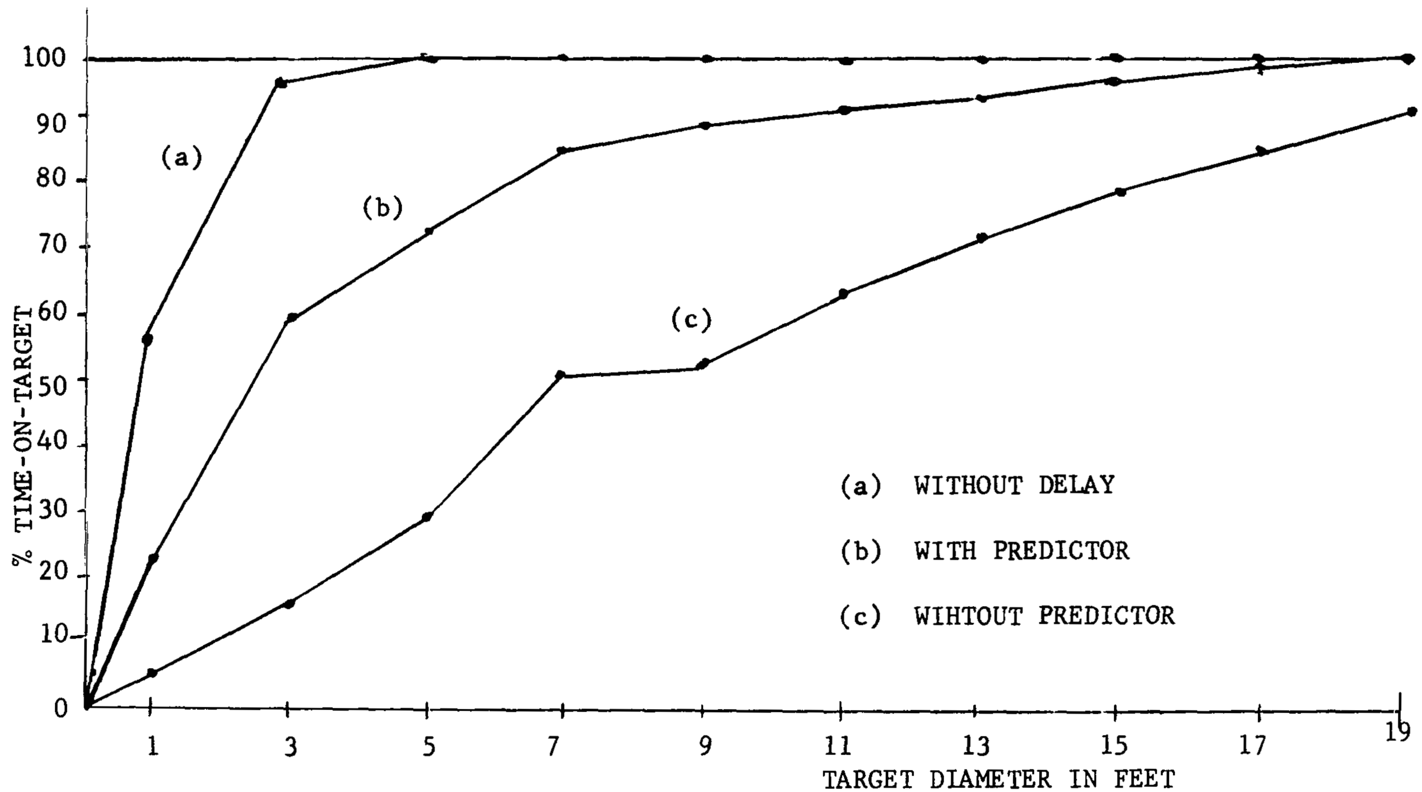


Fig. 31 TRACKING - DRIVER B

D. MAZE EXPERIMENT

1. TEST PROCEDURE

The method of scoring the maze experiment is somewhat different than the method used to score the tracking experiments. Between wickets, drivers are free to choose any means of maneuvering that they desire. Their performances in these open areas, however, influence their approaches to each wicket, and hence, the accuracy with which the wickets are negotiated. The wickets themselves consist of two parallel rows of traffic cones and are 15 feet long by 10 feet wide. The wickets were positioned as shown in Fig. 32. 90^o of turning effort is required to travel between wickets 1 and 2, 180^o of total turning effort between 2 and 3, and 270^o of total turning activity between 3 and 4. This permits a comparison of approach complexity on the ability to successfully thread the wickets. As with the tracking experiments, the maze performances were recorded on film. In the same way, the film record was converted to a permanent tracing of the runs, using a scale of one inch equals 15 feet, and then the tracings were photographically reduced for presentation with this paper.

The viewing angle (53^o) of the television camera mounted on the vehicle restricts the angle of vision to the extent that the wickets are lost to view when driving between wickets. If the wickets were positioned so that each could be kept in the field of vision during the entire run from the preceding wicket, the situation would be similar to placing the wickets along the curve used in the tracking experiment.

The maze shown in Fig. 32 deliberately spaces the wickets far apart so that involved maneuvering between them is required. The fact that the goal may be lost from sight during maneuvers in the open spaces is part of the handicap imposed on the drivers. This handicap simulates the real-life situation where drivers seek limited objectives which may be temporarily obscured from view during maneuvers.

In most cases, the run between wickets involves a distant view of the objective followed by a period in which the operator drives blind and must base his steering decisions on his original view of the goal. Finally, as the driver approaches a wicket, it reappears, and he has a brief period in which he can adjust his approach.

One means of evaluating driving skill is to study the performance tracings. In doing so, the various parts of the action should be observed. Realizing that the angle of view of the vehicle's television camera is 53^o centered about the tangent to the path of travel, the extent of the blind period of driving can be observed. This procedure shows the vehicle location where the observer recovers his view of each wicket as it is being approached. It should also be remembered that when driving with a signal transmission lag, driving instructions are programmed a

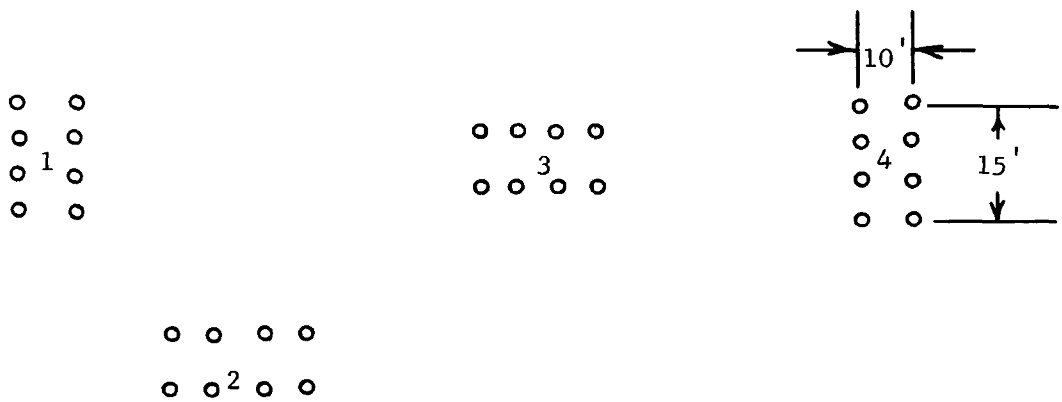


Fig. 32 MAZE LAYOUT

considerable distance beyond the point at which the wicket first is seen. Last minute maneuvers based on this view can not occur until the vehicle has travelled this extra distance representing one delay period of travel. At a speed of 7.1 feet per second, and with a delay of 2.6 seconds, the advanced point leads the vehicle by 18.3 feet. On a number of tracings presented, the points A and B are shown for convenience on the wicket approaches. These letters, respectively, indicate the place where the driver first recovers his view of the wicket, and the point beyond which his next steering command can take effect.

Scoring within the wicket is achieved by weighting the accuracy with which the wickets are negotiated. Fig. 33 shows the weighting arrangement used. Sinusoidal weighting is used to provide a high score for driving through the wickets cleanly, to give a slight increase for centering the course as the drivers tried to do, and to give a small credit if the traffic cones were hit but the performance was close to succeeding. In looking at such numbers, it is well to consider the influence that the blind portion has on the quality of the approach. In some cases the approach is so poor that it is impossible to drive through a wicket. In these cases, the low score is almost entirely an indication of poor approach rather than poor judgement after the objective reappears in view.

2. MAZE EXPERIMENT DATA

The results of the maze experiment are shown in Figs. A12 through A25. As indicated by the arrows in the drawings, some runs were made from left to right in the wicket sequence of 1 through 4, and some were vice versa. This gives an opportunity to compare the two directions of travel between each wicket pair. The scoring of steering accuracy through each wicket is shown in Table 3. A subjective rating is included for each record to indicate if the driver had an excellent (E), good (G), poor (P), or no (N) chance of negotiating each maze when it appeared in his field of vision. The photographic record of Driver A's run without delay did not come out. However, the written records indicate that he drove the vehicle through the wickets without difficulty.

A great deal can be learned about driving performance by following the vehicle behavior shown on the tracings and by reconstructing the problems facing the driver during each maneuver. When examining each drawing, the places where the operator is driving blind can be separated from those where he can see his objective. To illustrate the method of analysing curves, two experimental runs are considered in detail in the following paragraphs. Comparative maze performances are shown in Fig. 34. The traffic cones forming the wickets are shown as dots. Radiating lines around these dots indicate the traffic cones that were knocked down in each experimental run.

Fig. 34(b) is a performance by Driver A steering the vehicle from left to right through the maze. A signal tranmission lag of 2.6 seconds was used and the driver did not have the benefit of the predictor. The run starts with an excellent chance of getting through the first wicket without difficulty. The driver's objective was to make a right turn

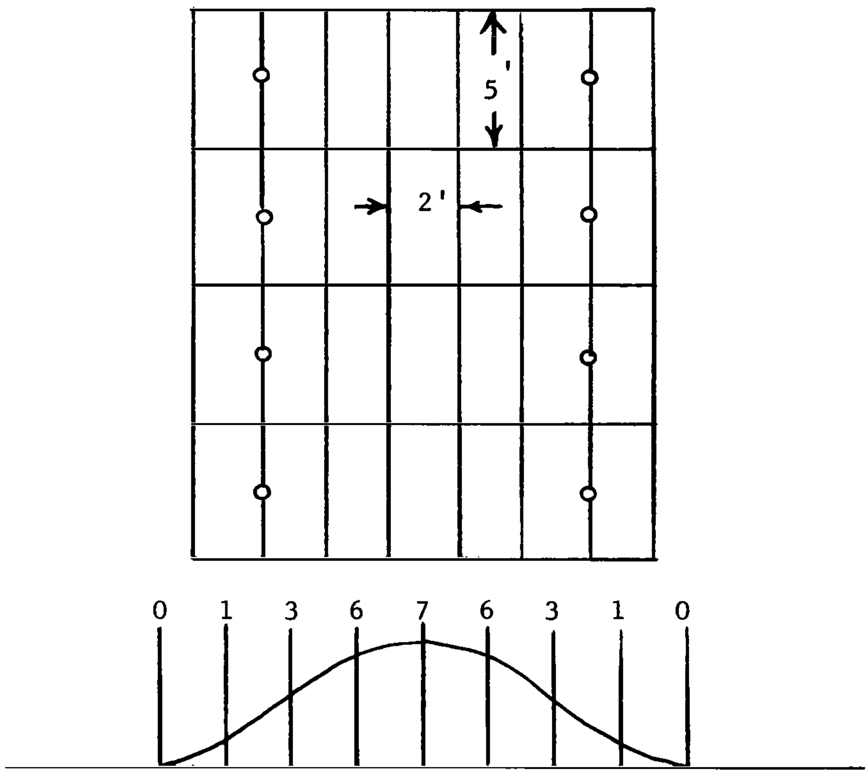
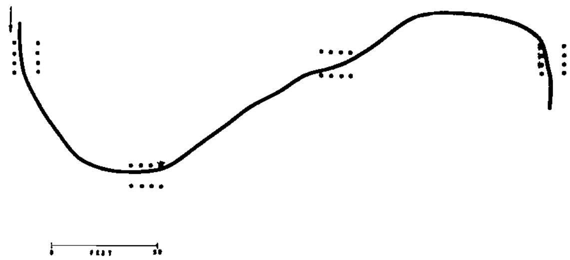


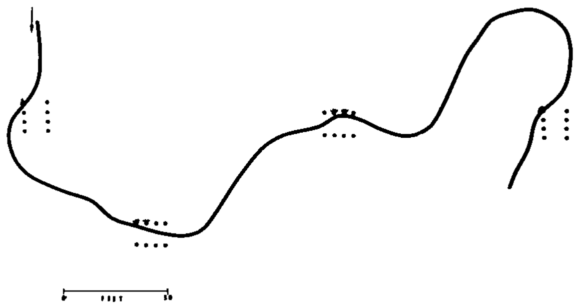
Fig. 33 MAZE SCORING

FIG.	DRIVER	SECS. OF SIG. TRANS. LAG	WITH PRED.	DIR.	WICKET SCORE I	II	III	IV
A12	A	2.6	no	→	2 E	24 E	20½ E	2 G
A13	A	2.6	yes	→	28 E	25½ E	26½ E	5 P
A14	A	2.6	yes	→	---	27 E	24 E	2 N
A15	A	2.6	yes	→	26½ E	27½ E	27½ E	0 N
A16	A	2.6	yes	←	27 G	12 N	18 G	25 G
A17	A	2.6	yes	←	0 P	27 G	22½ E	25½ G
A18	B	0	no	→	24½ E	22½ E	22 E	18 P
A19	B	2.6	no	→	22 E	14 G	17 G	10 G
A20	B	2.6	yes	→	11 P	10 P	19½ G	13½ P
A21	B	2.6	yes	→	26 G	13½ G	11 G	5½ N
A22	B	2.6	yes	←	23½ G	12 P	21 G	25 G
A23	B	2.6	yes	←	9½ G	20½ P	19½ E	25 G
A24	B	2.6	yes	←	20 G	26 G	17 G	25½ E
A25	B	2.6	yes	←	13½ P	27 G	25 G	23½ G

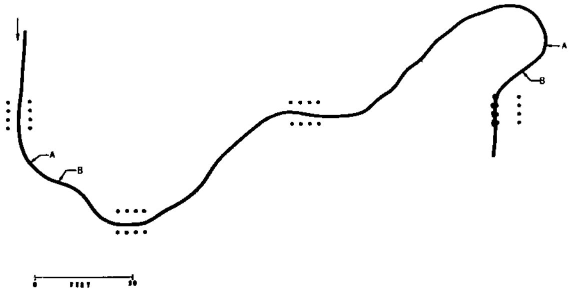
TABLE 3 MAZE SCORING CHART



(a) WITHOUT DELAY



(b) 2.6 SEC. DELAY - WITHOUT PREDICTOR



(c) 2.6 SEC. DELAY - WITH PREDICTOR

Fig. 34 COMPARISON OF MAZE PERFORMANCE

immediately after passing through the wicket so that he would have more maneuvering room for his approach to the second wicket. Unfortunately, he misjudged the effects of the signal transmission lag, made the turn too soon, and drove through the side of the wicket. However, this poor maneuver did leave him with an excellent chance to drive through the second wicket correctly. The second wicket came back into the driver's view as he was completing the left turn that followed the original right turn. By that time, steering instructions had already been programmed to carry the vehicle to the next sharp bend to his right.

The quick maneuver in front of the second wicket was made immediately by the driver. It was close to succeeding. Likewise, the third wicket was almost negotiated without difficulty. The magnitude of the corrective action taking place within the wicket is a demonstration of the exaggerated motions that generally occur for unaided driving with delay. The extent of the blind driving period between wickets 3 and 4 is much greater than between the other wickets. The driver saw the wicket as he was completing the larger turn in front of it. By then, steering instructions had been sent to steer the vehicle close to the wicket. When the driver's steering adjustment commands had reached the vehicle, the effect was to oversteer, causing the vehicle to miss the wicket by a greater margin than if the instruction had not been sent.

Fig. 34(c) is identical to the preceding situation except that the driver had the benefit of the predictor. Little action was needed to get through wicket 1. Wicket 2 was first seen when the vehicle reached point A, and since already programmed instructions committed the vehicle to continue on to point B, the wicket threading adjustments occurred between point B and the wicket. Wicket 3 was also threaded well, the driver having plenty of time and opportunity to make entrance adjustments. Between 3 and 4 the driver was plagued by the problem of having to perform a great deal of blind maneuvering. The wiggles indicate an uncertainty on his part as to when to make blind turns. The wicket was overshot during this period and reappeared when the vehicle reached point A. At this time instructions had already been sent to steer the vehicle to B as the driver doubled back, looking for his objective. When the driver saw the wicket, he made a quick maneuver using the minimum turning radius, and nearly succeeding in passing through the wicket. Had he seen the wicket a little earlier, he would have probably driven through it successfully.

This kind of analysis indicates that the predictor is of help for the tight maneuvers required in entering and driving through the wickets. The drivers reported that they generally did not use the predictor during blind periods, since they were driving in unobstructed areas. The major difficulty was that they did not have sufficiently advanced views of the upcoming wickets. A wider angle lens on the television camera seems to be essential for the success of real-life situations.

The scoring numbers partly indicate the ability to thread the wickets and partly reflect the success of the maneuvers during the blind periods. These numbers do not show any particular difference between the 90^{o} maneuvers between wickets 1 and 2, and the 180^{o} maneuvers between 2 and 3. They do show, however, that it is more difficult to maneuver into a good position from which to enter wicket 4. They also show that it is more difficult to perform 270^{o} maneuvers from 3 to 4 than the reversed situation of going from 4 to 3. This is related to the fact that there was more time for adjustment after the objective was sighted when driving from wicket 4 to wicket 3 than there was when going from wicket 3 to wicket 4.

E. RANDOM FIELDS

As one moves from tracking tests towards driving in a field of scattered obstacles, it becomes more difficult to express conclusions in number form. One possibility is to count obstacle hits. Another possibility is to measure the time required to reach a distant goal. A particularly sticky problem is how to score the combinations of driving time and obstacle hits. The weighting decision is similar to trying to decide how many oranges equal one apple. The relative importance is dependent on how the problem is presented to the test driver. If he is told to negotiate an obstacle field cleanly, the time of the run would be the deciding factor, and any runs with obstacle collisions would be marked as total failures. On the other hand, if the problem is presented as measuring the accuracy of driving through a uniform field of obstacles, the number of collisions would be a primary measure of success.

With an eye to future testing, we conducted some exploratory tests of driving through a random field of obstacles. This experience indicated that it will be important in future study to observe the effects of varying densities of obstacle fields on driving performance. In this exploratory look into random fields, the illusion of a "floating" prediction marker was encountered, This is the result of having to superimpose two television pictures, with the inevitable result of ghosting. To illustrate: when the prediction marker is driven around behind an obstacle, it is not hidden from view by the obstacle, but is seen as if the obstacle were transparent. The driver is then confronted with the problem of having to convince himself that the predicted spot lies on the ground behind the obstacle instead of "floating" in the air in front of the obstacle.

F. SUBJECTIVE REACTIONS

Several driver reactions and experiences have already been mentioned. In this section subjective reactions are discussed.

The first item concerns the method of steering. As mentioned in the description of the equipment, a displacement control is used. This is in keeping with references that show that displacement controls are better than velocity controls and other higher order controls. At the same time, the displacement control requires continual turning action and differs in this respect from automobile behavior with which both drivers were acquainted. They immediately concluded that they would prefer an automobile type steering. In fact, one driver prepared a sketch of how the steering could be modified to the automobile arrangement. However, after some experience with the displacement controls, both drivers found this arrangement to be desirable. Driver A reports that he likes the extra steering activity; it keeps him busy and loose. Driver B feels that a displacement control permits more stable driving. Since the operator has to turn the steering wheel through all the angular changes of the vehicle, he feels that this effort tends to inhibit over-steering and instability.

When driving with a signal transmission lag and no predictor, the drivers found it helpful to steer in a burst of activity. Here they would command a large turn and then wait, if possible, to observe the results before making the next turn. Driving performance improves when they have an opportunity to separate the job into a series of isolated maneuvers.

When driving without the predictor, the drivers also made use of relay noises that occur with each input command. By listening to these clicking noises, they received an immediate feedback, reinforcing the positioning feedback obtained through their hands, describing the amount by which the steering wheel was turned. They did not use the audible feedback when the predictor was used, though it did help them in determining both the magnitude of each turn and the rate at which each turn was made. With the predictor, they preferred to concentrate on the motion of the prediction marker. These observations can be summarized by saying that the operators preferred the visual feedback of watching the prediction marker. In the absence of the marker, they used the audible feedback to reinforce the positioning feedback of turning the steering wheel.

The next item to consider is the television display. Both the drivers feel that their performances are adversely affected by not having a wider viewing angle. The effects of the present 53^{o} viewing angle are described in the maze experiment discussion. It is strongly recommended that means for increasing the angle of vision be considered and used, if possible, in future studies.

In the present study we have not included the variable of picture quality. In anticipated missions, the television pictures may be of poor quality. The operator's ability to drive with poor pictures should be investigated. In the course of our training period, we experienced some occasions of poor television pictures. Driver A was able to drive well with a surprisingly poor picture. As long as he was able to identify fragments of the white line, he was able to track it adequately. These observations are incidental to the primary objective of this phase of the project, but they do indicate ability to drive under trying conditions.

Driver A sits very close to the screen in an effort to relate his eyes to the picture as the vehicle's television camera is related to the scenery. He feels that this increases his sensation of being involved in the operation.

Both drivers report that they are not distracted by noises and other activities in the control station.

Both drivers find it an advantage to have a second person in the truck. They feel that it helps to relieve the tension. Since they are driving slowly, they would have time to consider the suggestions offered by an observer in the control station.

Both drivers would like to be able to stop and look around before entering involved areas. It is recommended that this capability be added to the equipment.

G. SUGGESTED AREAS FOR FUTURE WORK

1. RANDOM OBSTACLE COURSE

After the tracking and maze tests for this project were completed, a few exploratory tests were made with a random field of obstacles. This experience suggests an experimental study to determine the effects of increasing the density of a field of obstacles on driving performance. Upper and lower bounds of performance can be established by driving with and without signal transmission lag as a means for evaluating the predictor. For experimental purposes, a random pattern of obstacles could be developed and tests run with this random field expanded in a series of steps to provide fields of decreasing density.

Fig. 35 shows a speculation of performance. Comparing these three types of driving, it is reasonable to assume that performance will be the same for extremely low density fields and extremely high density fields. In the case of low density fields, no obstacles would be hit regardless of whether or not the vehicle is under precise control. In the case of extremely dense fields, a swath would be cut with or without precise control. For intermediate fields, however, the control offered by the predictor should make the difference between avoiding obstacles and occasionally intercepting them. The net result is that higher speeds could be maintained in medium density fields if a predictor is used. A future study is recommended for investigating this matter of field density and determining over what range the predictor offers a significant advantage.

2. COMPUTER SIMULATION

The present development is a simulation of a real-life situation, and, like all simulations. it contains some unrealities. The

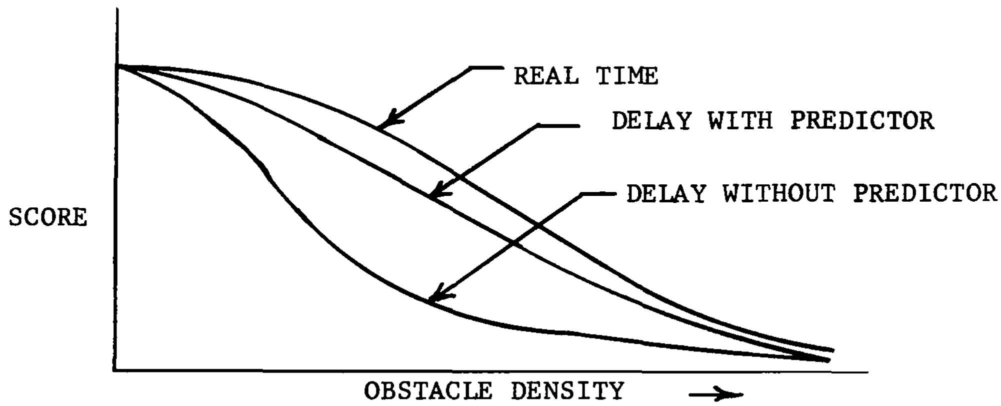


Fig. 35 SPECULATIVE OBSTACLE COURSE

advantage of the present arrangement over the laboratory simulations is that it permits a driver to experience the problems of driving a real vehicle with feedback through a television display. At the same time, the collection of field data is both time consuming and expensive.

It is possible that in future studies, a computer may be programmed to simulate adequately the experiences that are obtained by use of an actual vehicle. When this is done, the present equipment can be used to calibrate and check the validity of the computer simulations. Another possibility is to obtain laboratory tracking data as a means for expanding field data if the proper relationship can be found between the two.

H. CONCLUDING STATEMENT

This project has resulted in the development of a working predictor for the remote control of vehicles where there is a long signal transmission lag. The system was evaluated with a signal transmission lag of 2.6 seconds and a vehicle speed of 7.1 feet per second (nearly 5 mph). The results of the tracking experiments show that the predictor makes it possible for an operator to drive nearly as well with a signal transmission lag as he can drive with no delay at the same vehicle speed.

The experience gained with driving through a maze shows that the predictor is useful where precise maneuvers are required. When the predictor is in an open field, it is not needed or used, but when the driver approaches a wicket, he takes advantage of the extra control provided by the predictor.

Experience with the maze showed that a wider angle view of the landscape is needed for the vehicle's television camera. The 53° angle lens used hampered maneuverabilty since it is possible to drive the vehicle outside its field of vision. In many cases, the 53° angle of vision prevented the drivers from seeing the wickets until an insufficient time was left to steer the vehicle through them.

The equipment developed serves as an excellent base from which to conduct further studies into the problems of remote control with long signal transmission lags.

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APPENDIX A

TRACKING AND MAZE EXPERIMENTAL RUNS

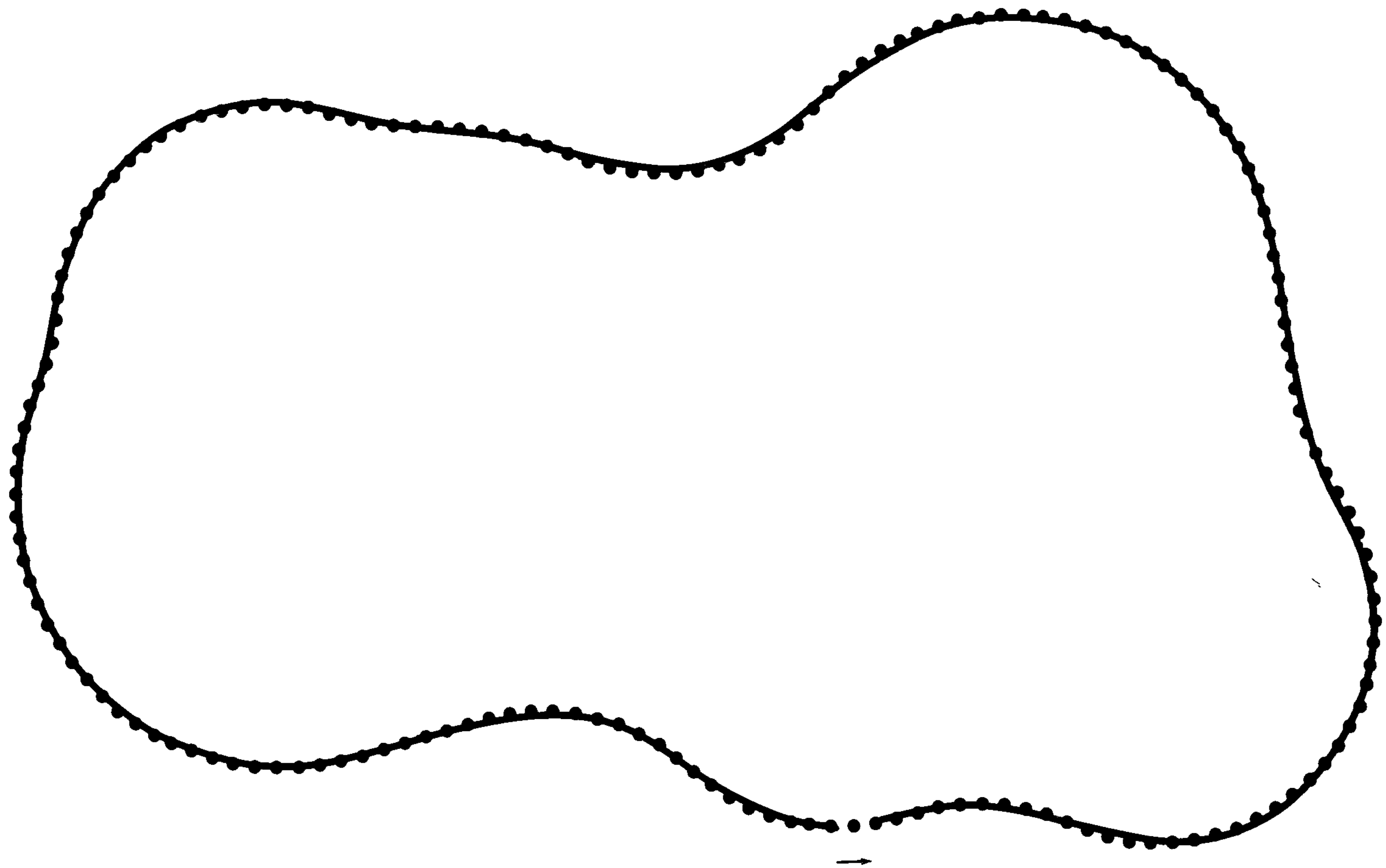


FIG. A1 TRACKING EXPERIMENT

7.1 fps 0 sec delay
DRIVER A WITHOUT PREDICTOR

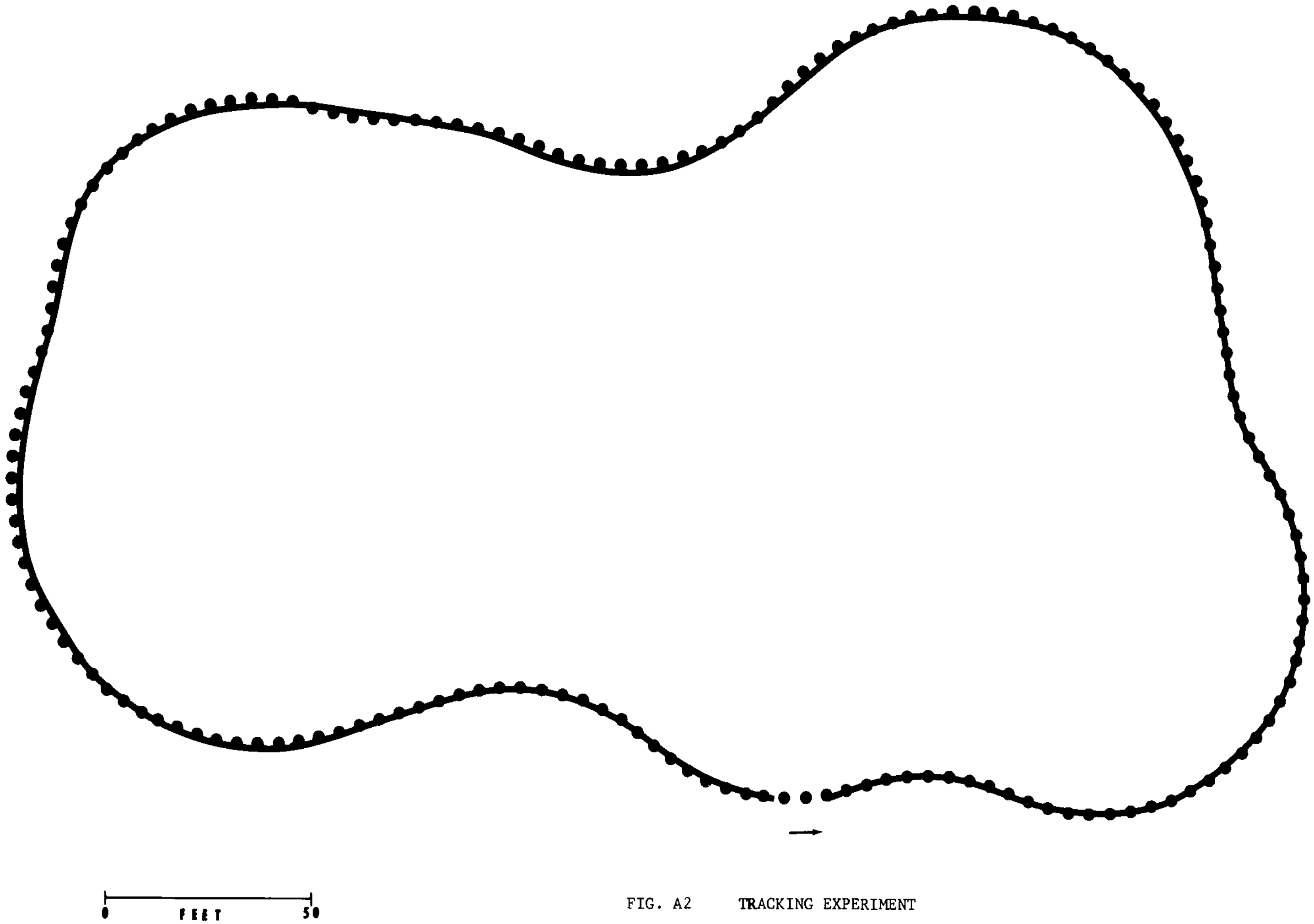


FIG. A2 TRACKING EXPERIMENT

7.1 fps 0 sec delay
DRIVER A WITHOUT PREDICTOR

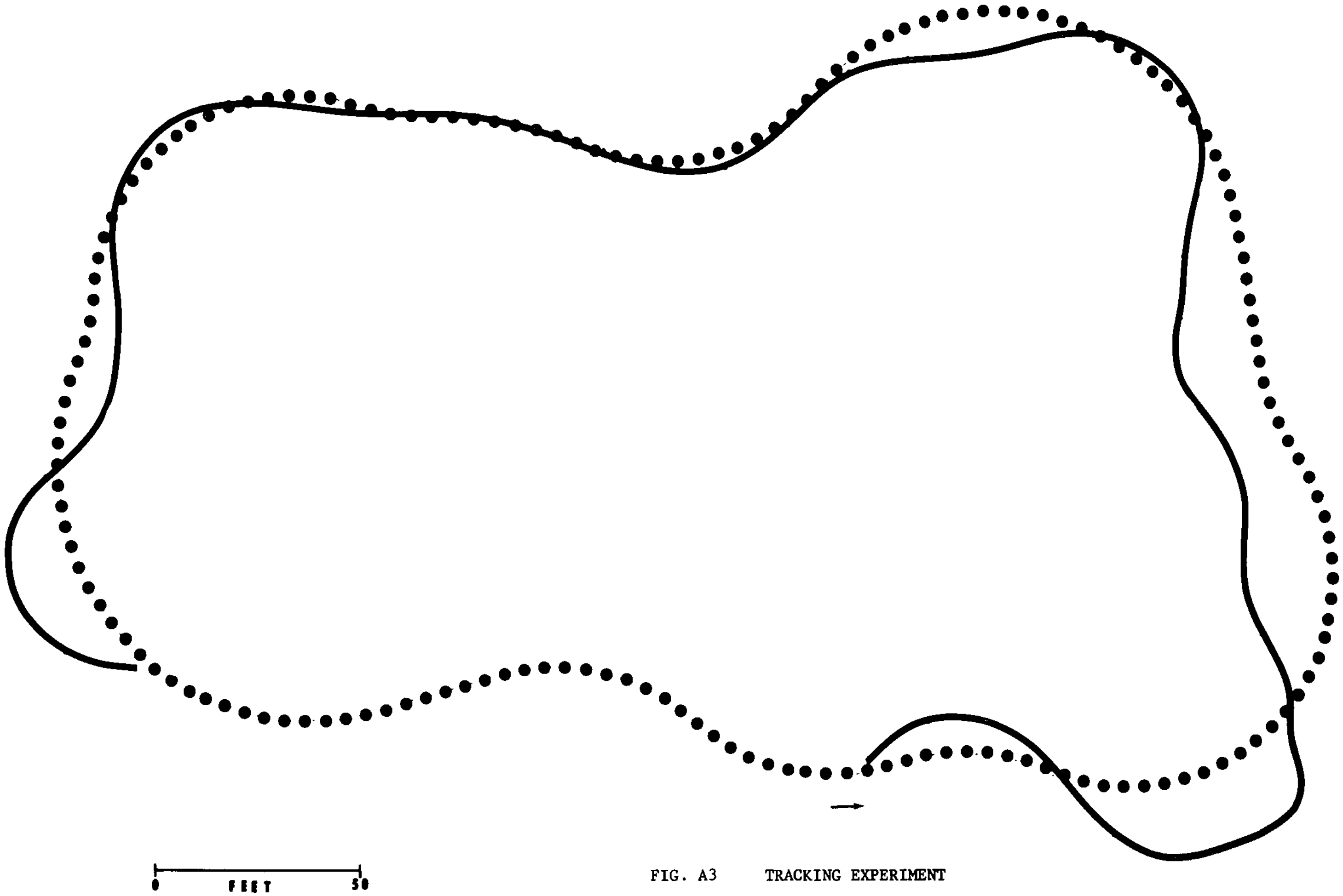


FIG. A3 TRACKING EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER A WITHOUT PREDICTOR

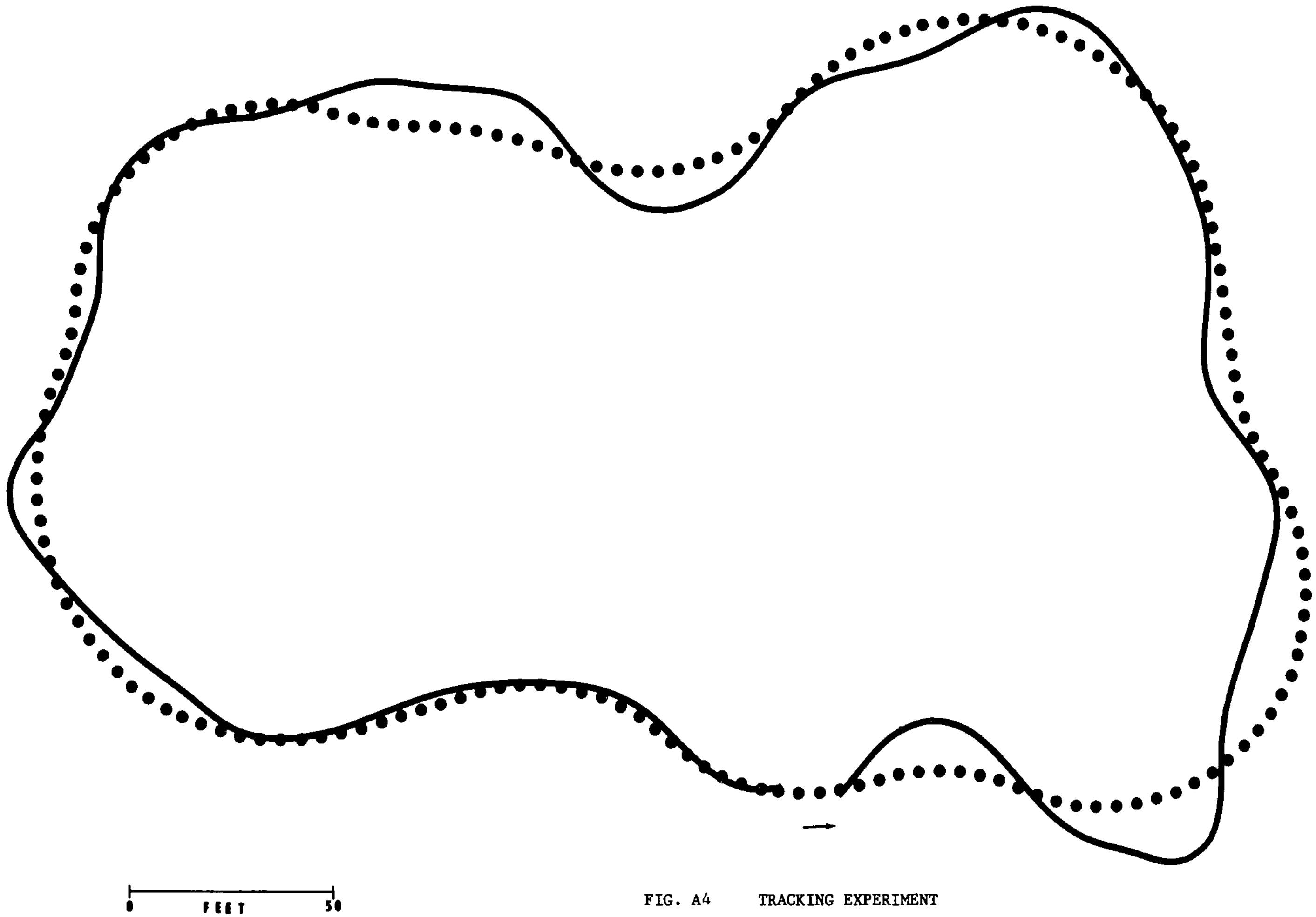


FIG. A4 TRACKING EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER A WITHOUT PREDICTOR

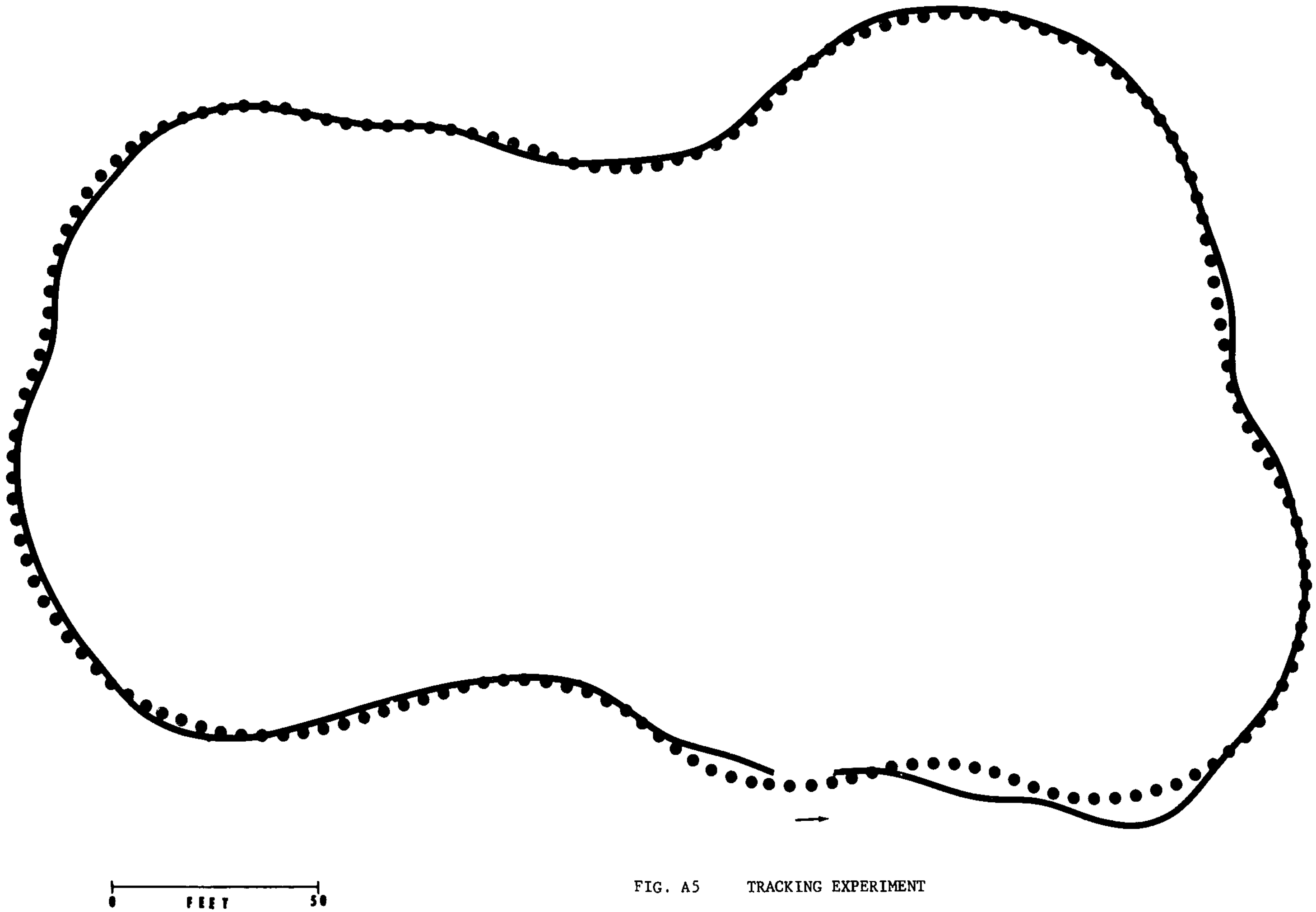


FIG. A5 TRACKING EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER A WITH PREDICTOR

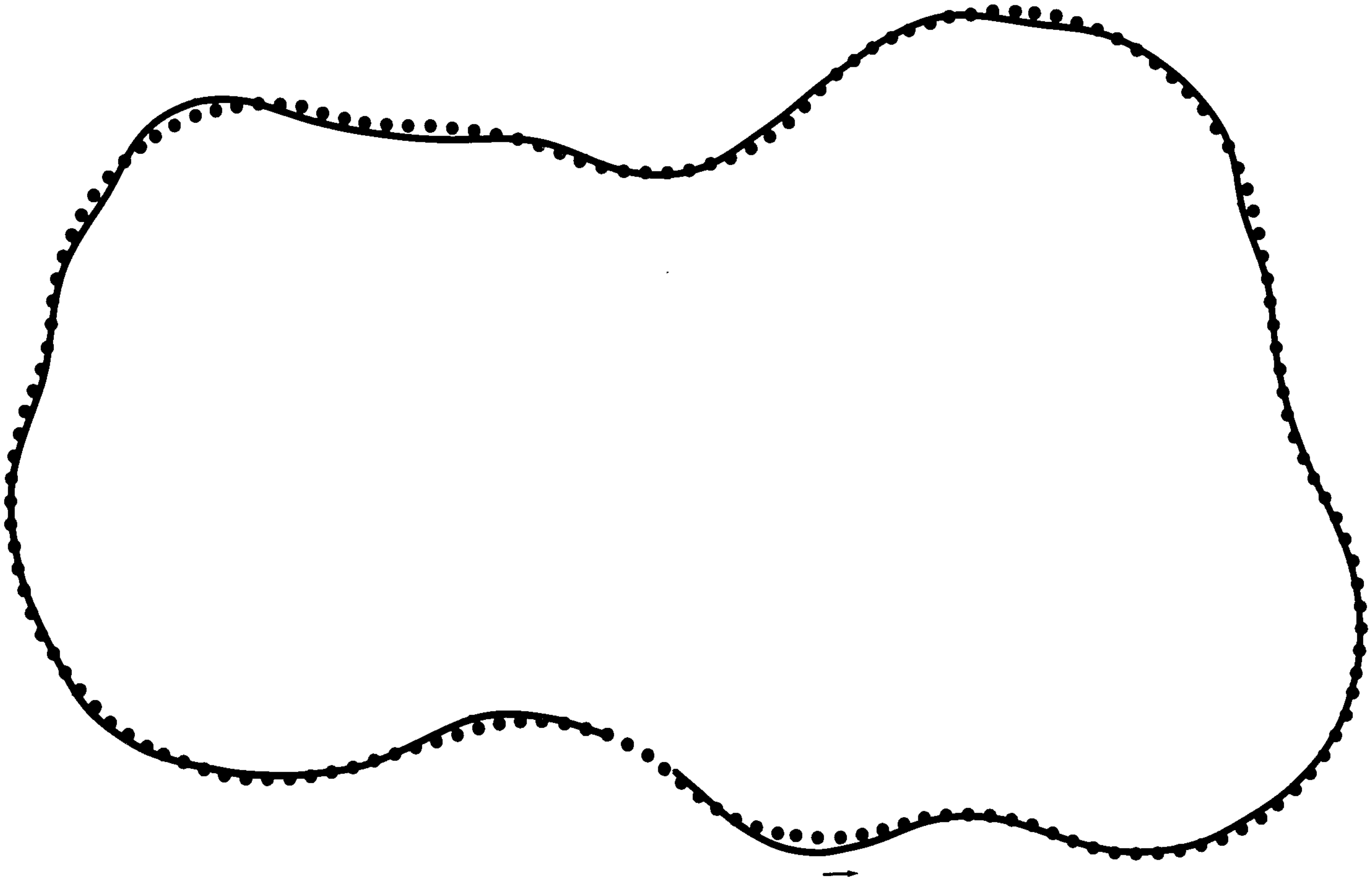


FIG. A6 TRACKING EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER A WITH PREDICTOR

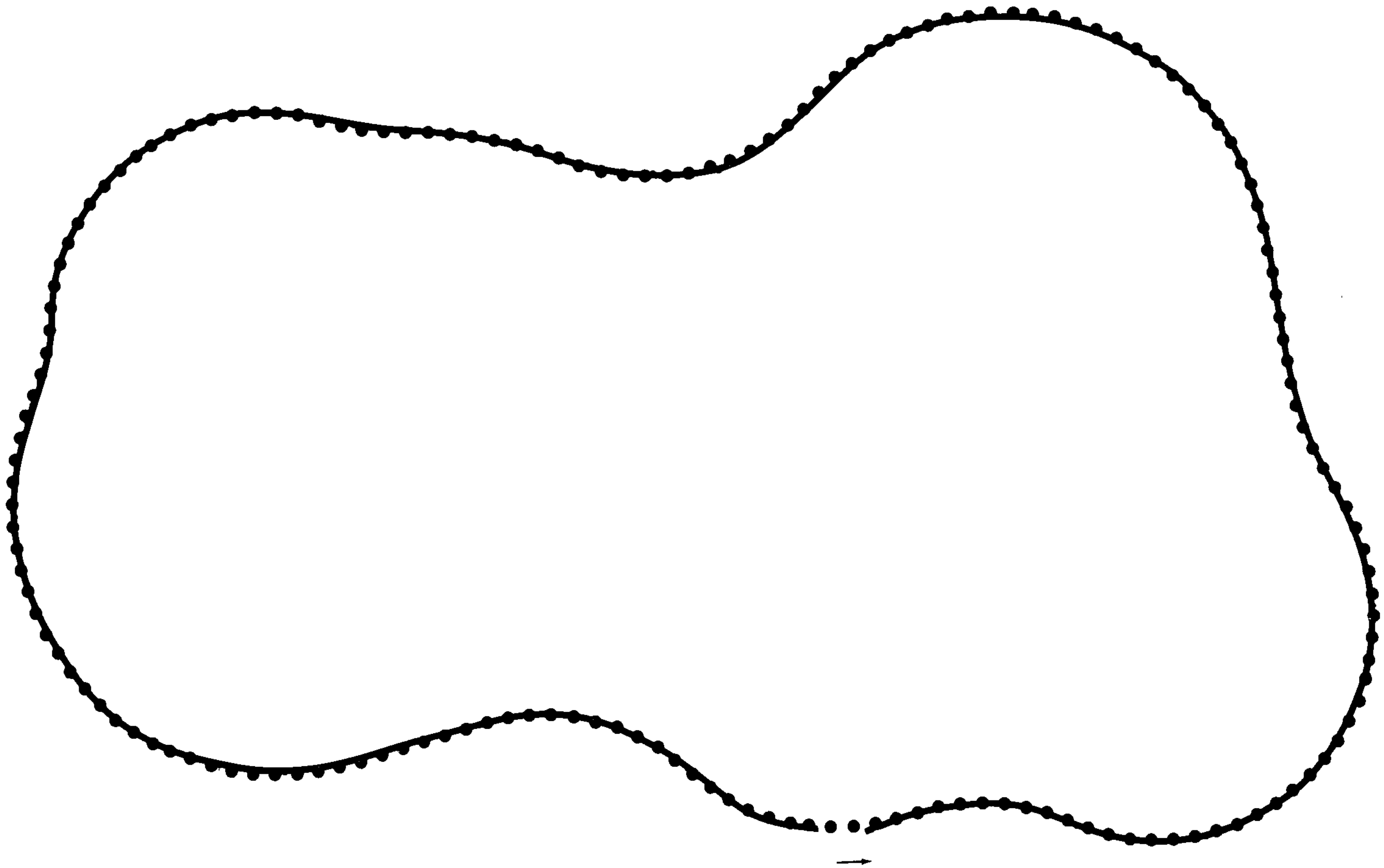


FIG. A7 TRACKING EXPERIMENT

7.1 fps 0 sec. delay
DRIVER B WITHOUT PREDICTOR

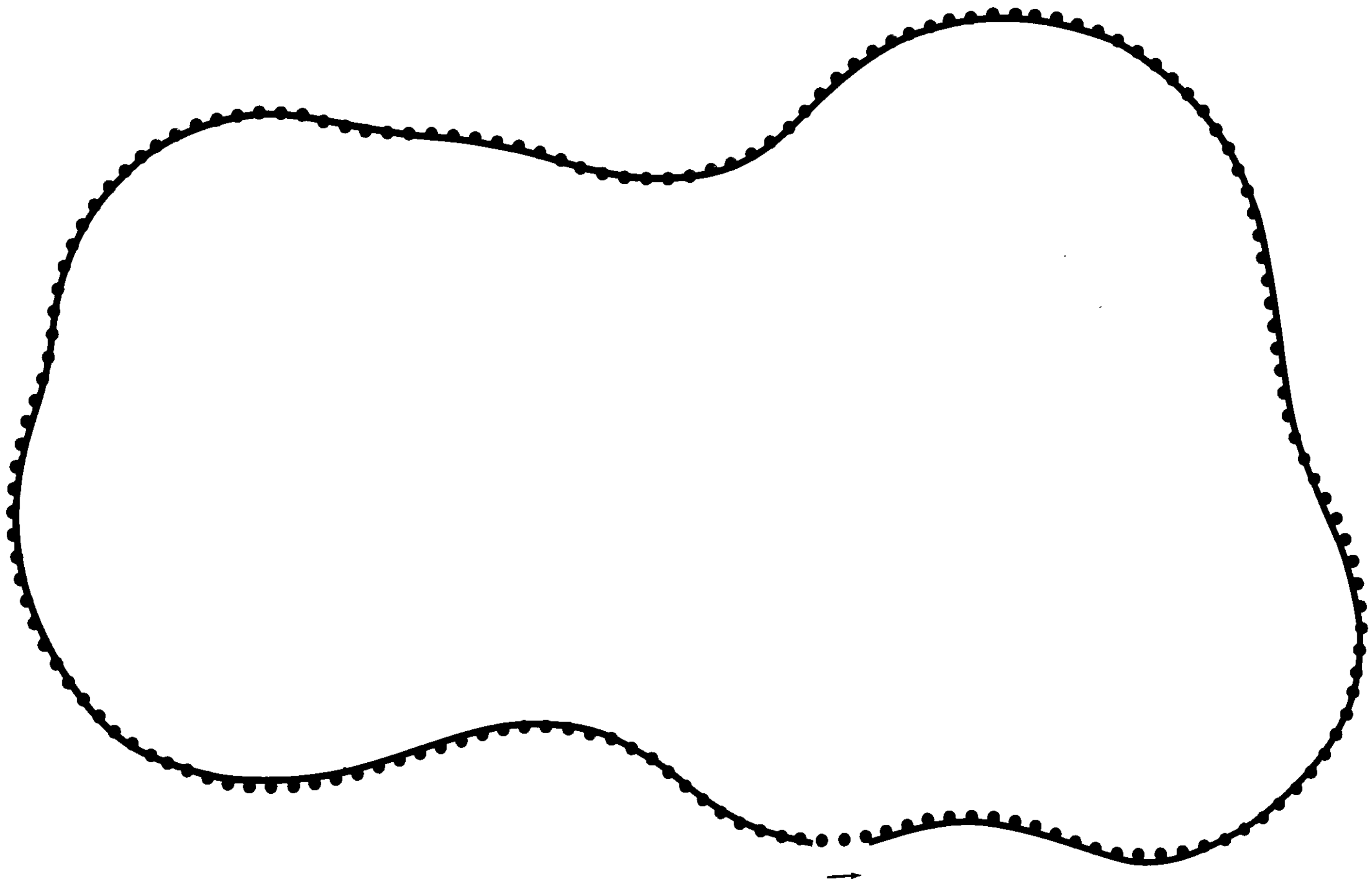


FIG. A8 TRACKING EXPERIMENT

7.1 fps 0 sec. delay
DRIVER B WITHOUT PREDICTOR

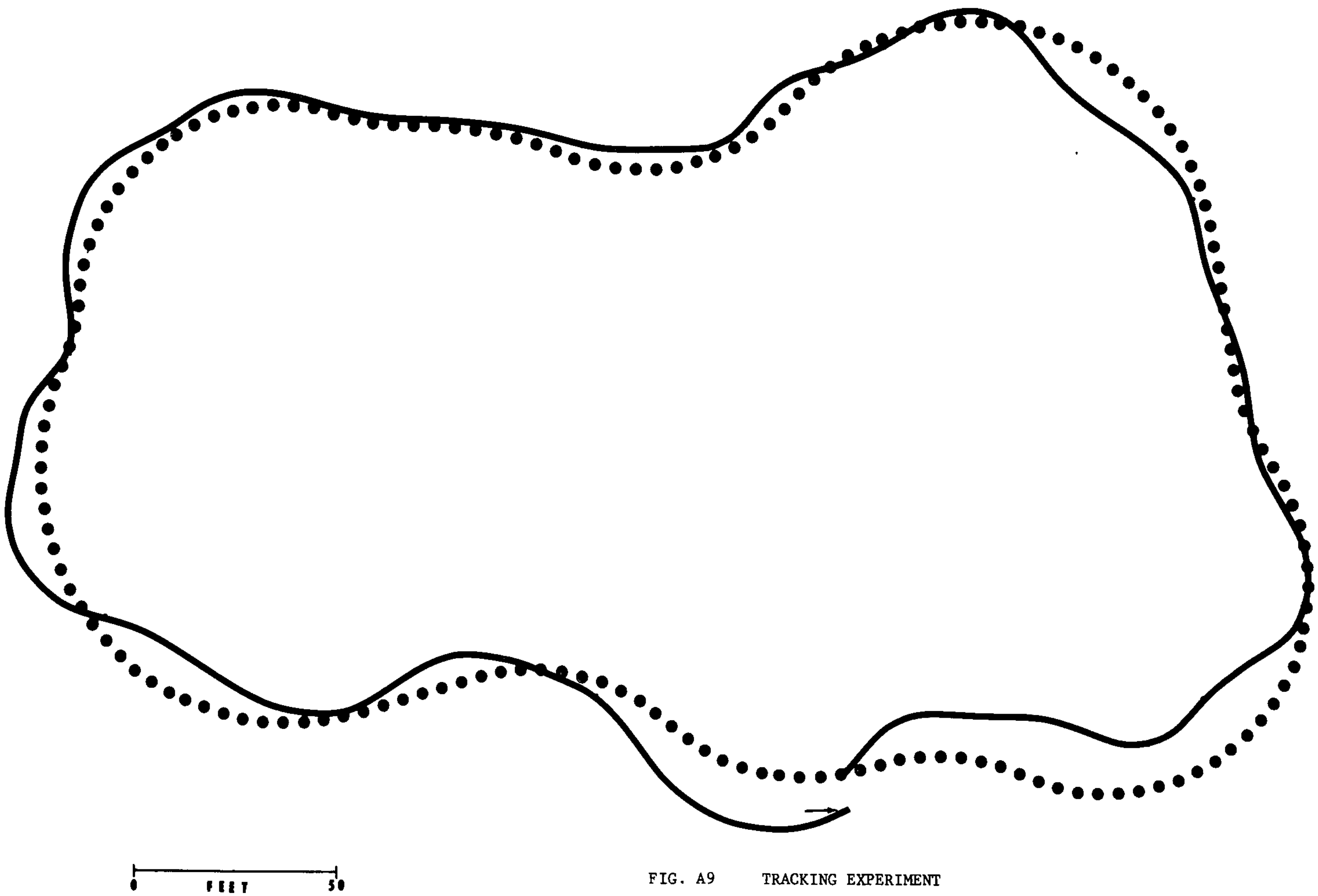


FIG. A9 TRACKING EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER B WITHOUT PREDICTOR

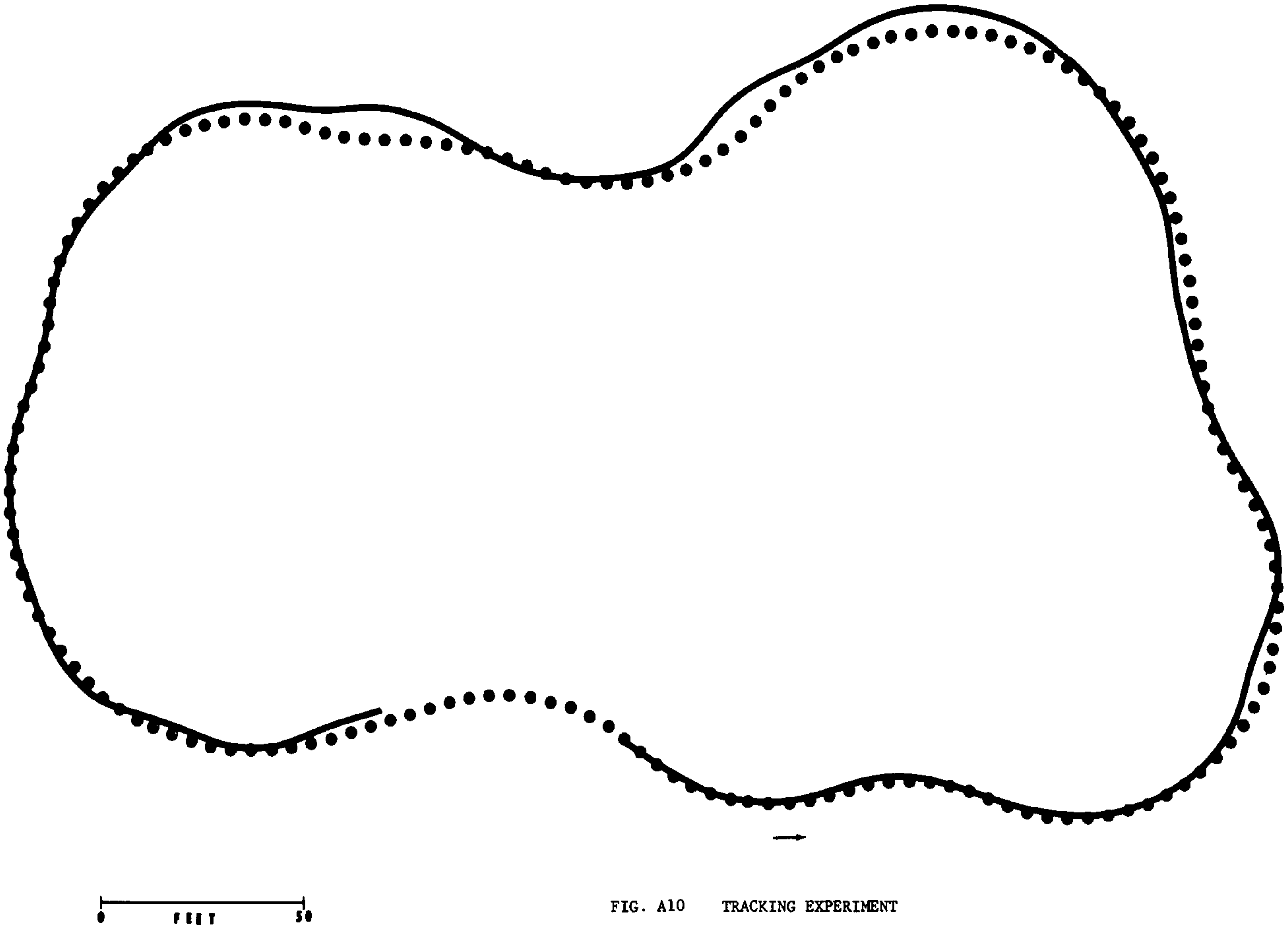


FIG. A10 TRACKING EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER B WITH PREDICTOR

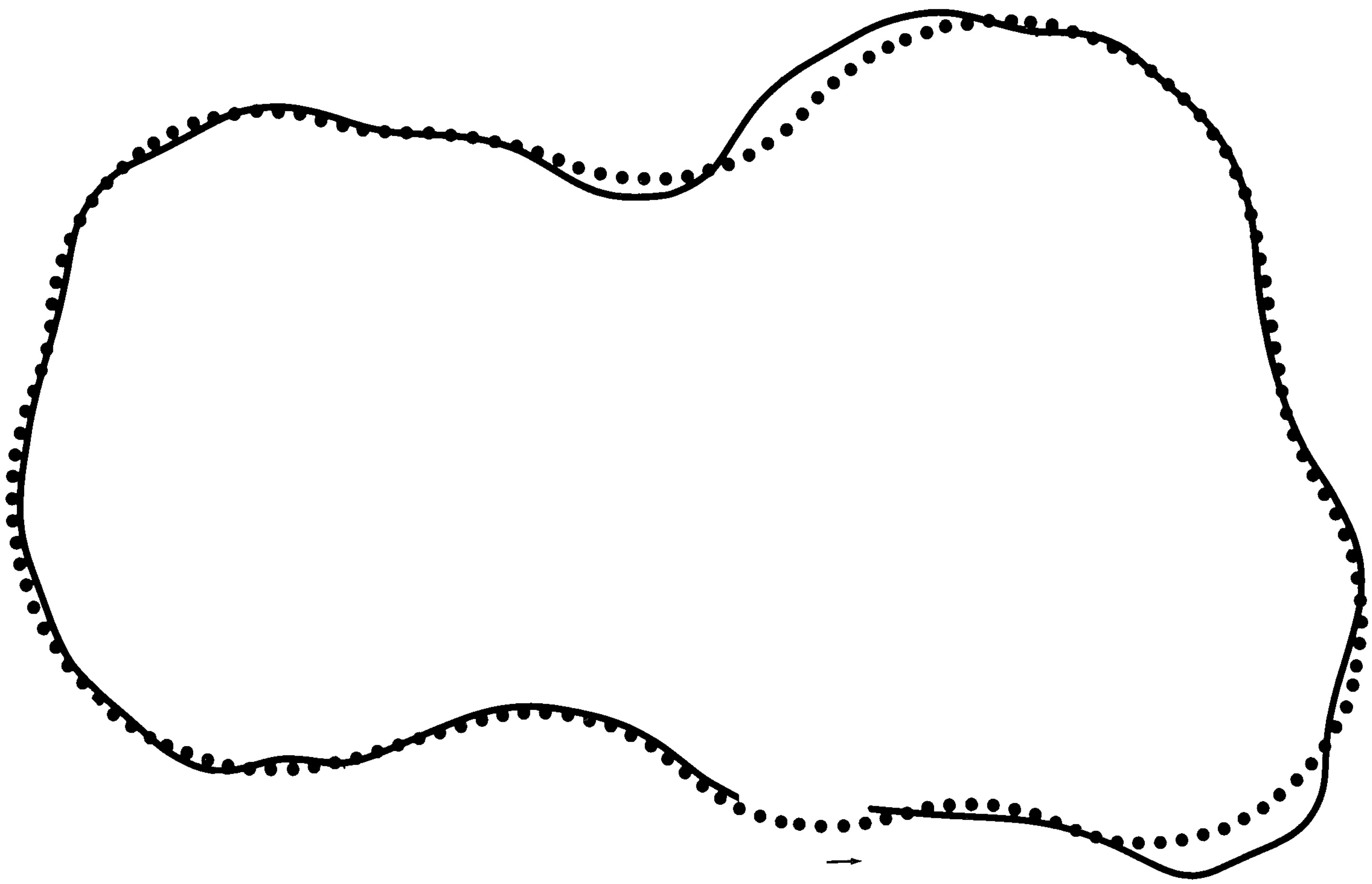


FIG. A11 TRACKING EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER B WITH PREDICTOR

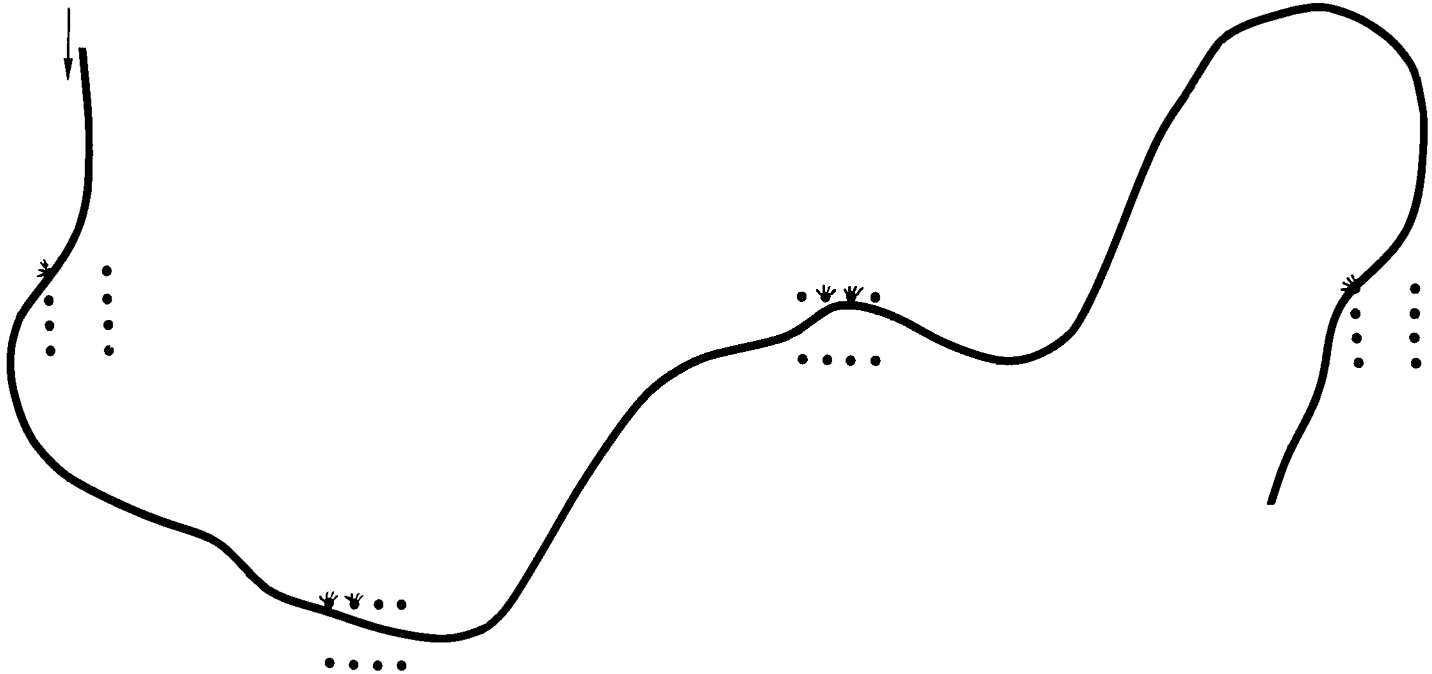


FIG. A12 MAZE EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER A WITHOUT PREDICTOR

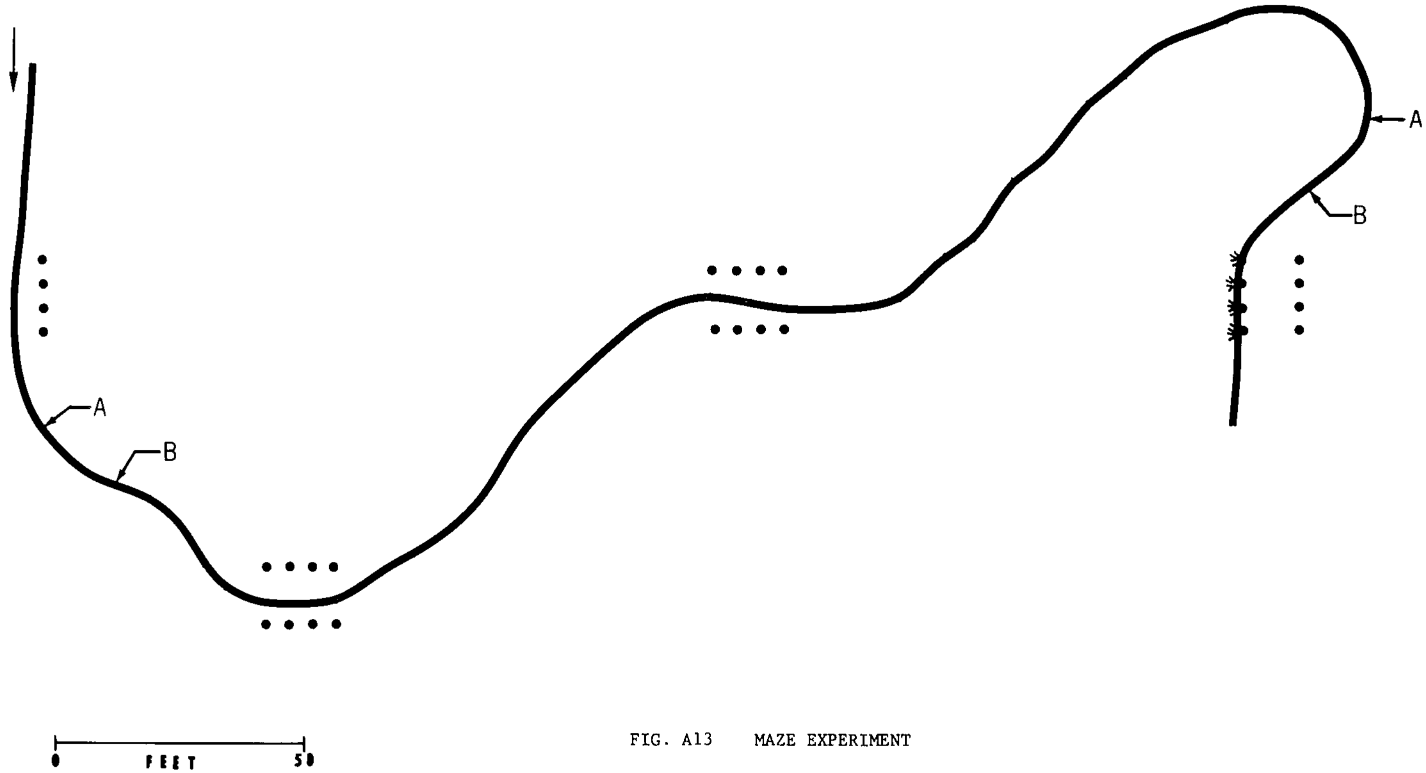


FIG. A13 MAZE EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER A WITH PREDICTOR

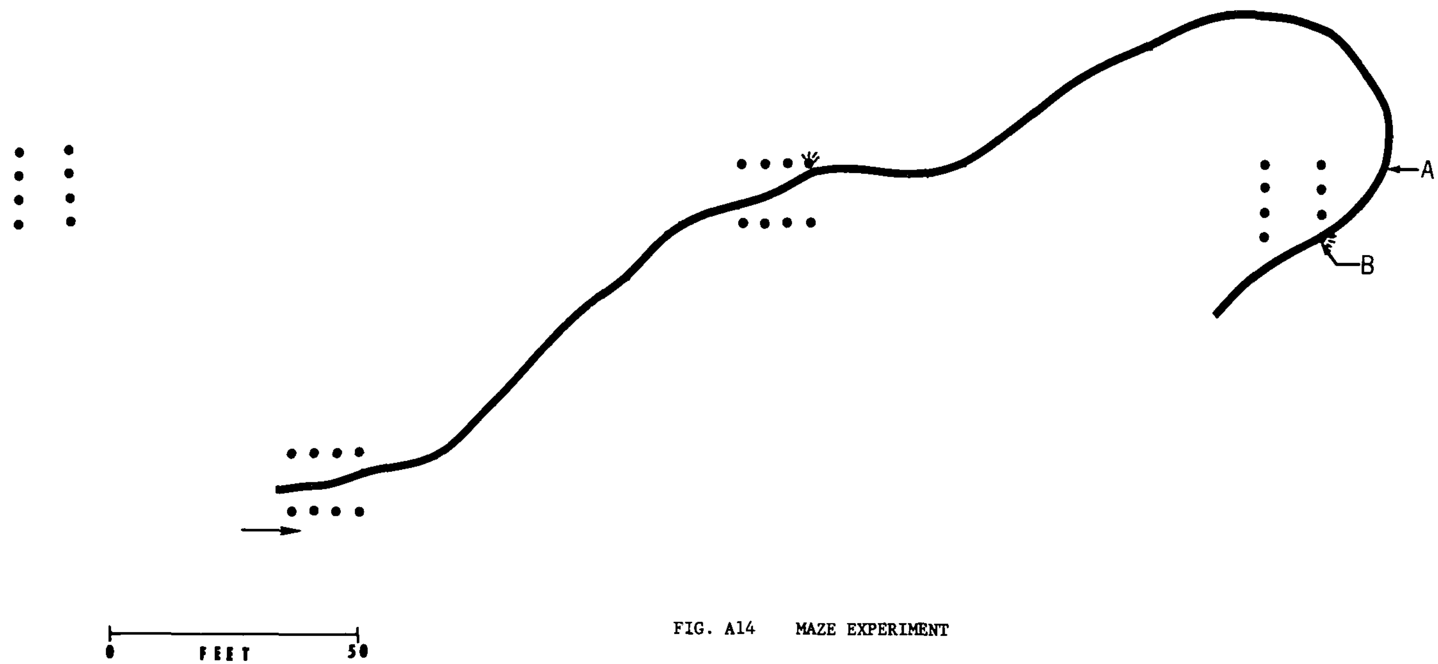


FIG. A14 MAZE EXPERIMENT

7.1 fps *2.6 sec. delay*
DRIVER A WITH PREDICTOR

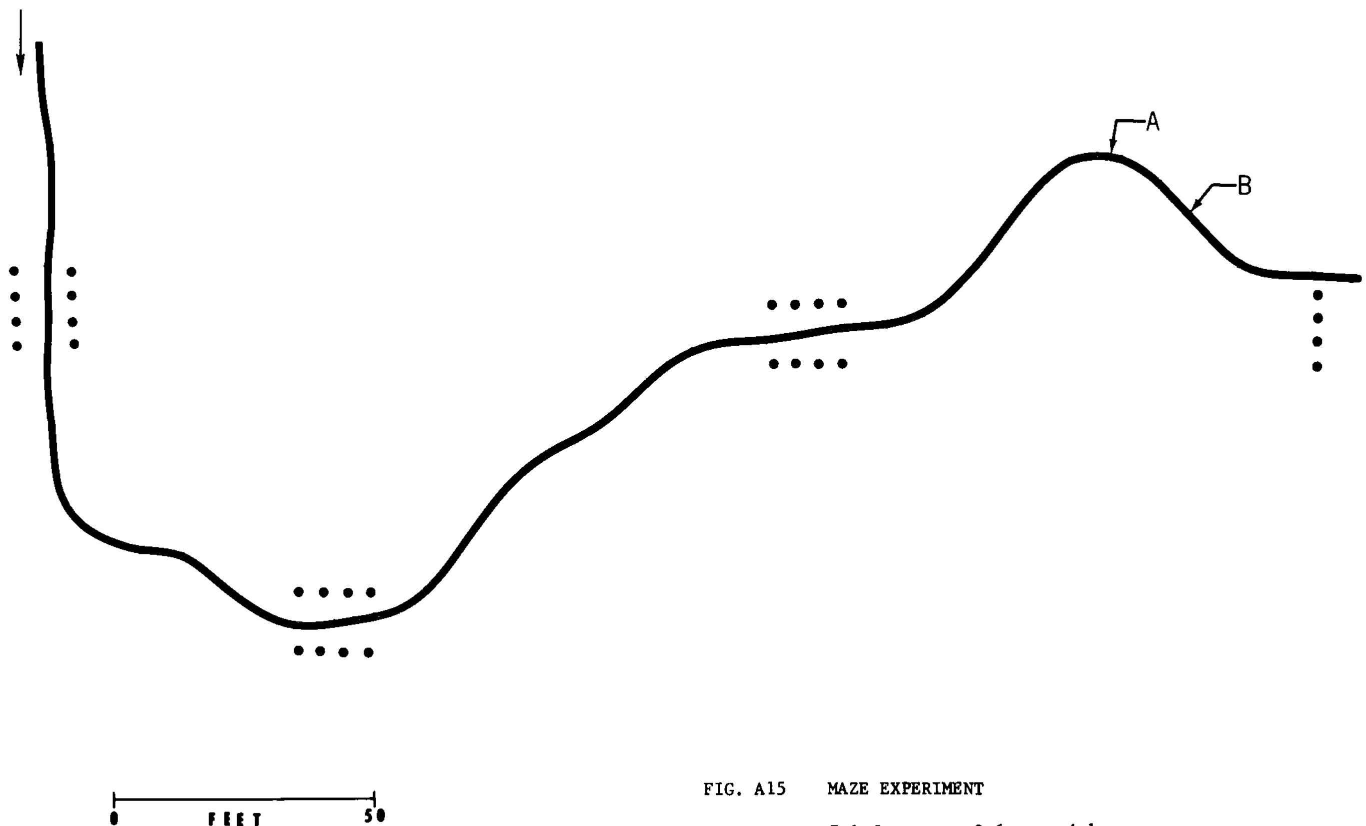


FIG. A15 MAZE EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER A WITH PREDICTOR

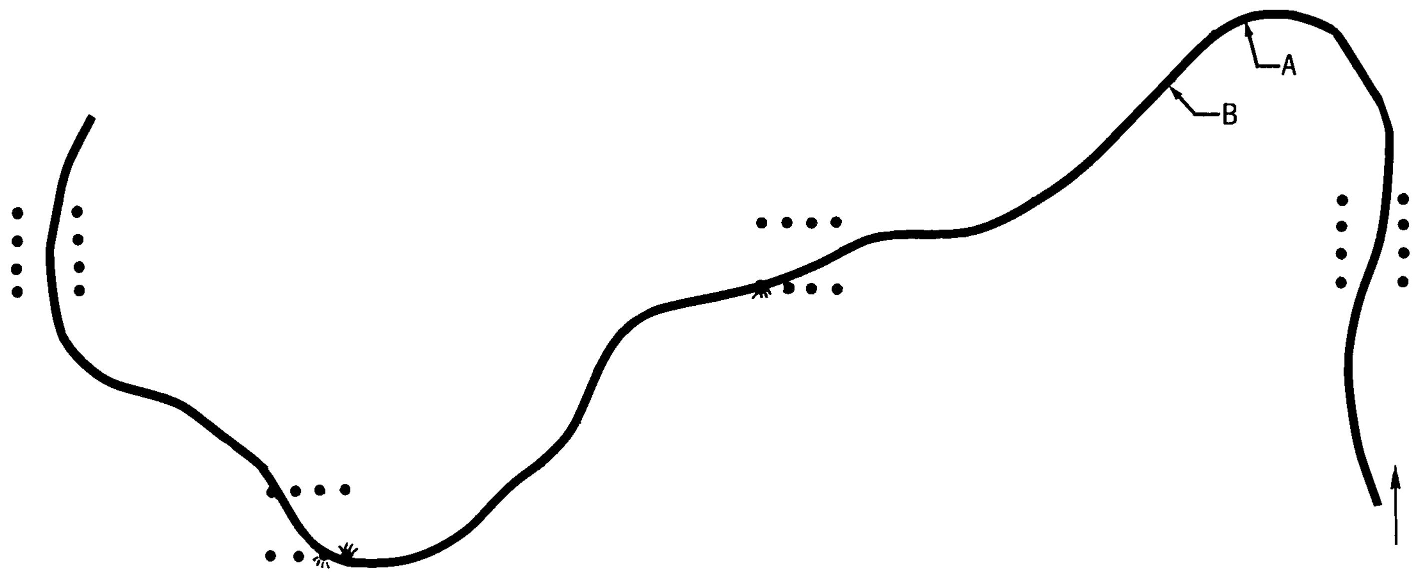


FIG. A16 MAZE EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER A WITH PREDICTOR

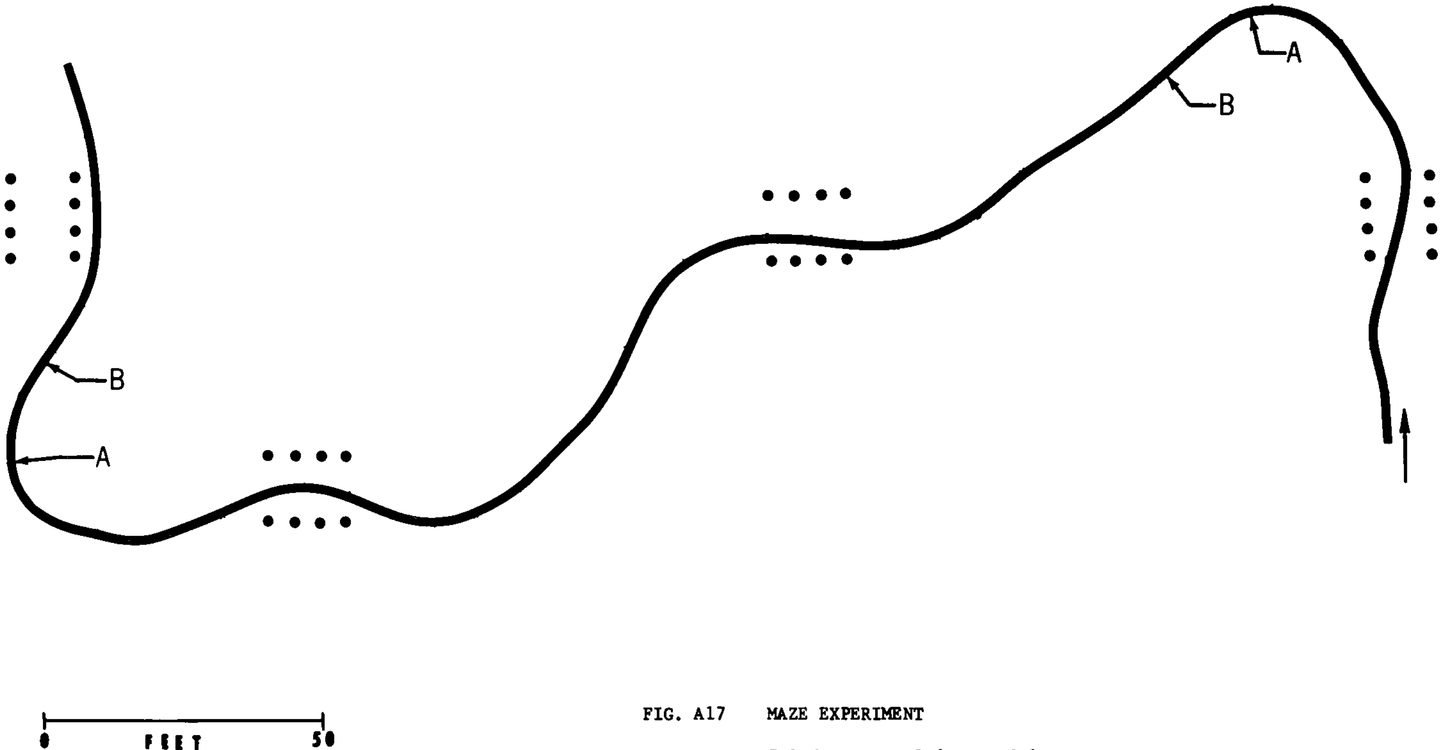


FIG. A17 MAZE EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER A WITH PREDICTOR

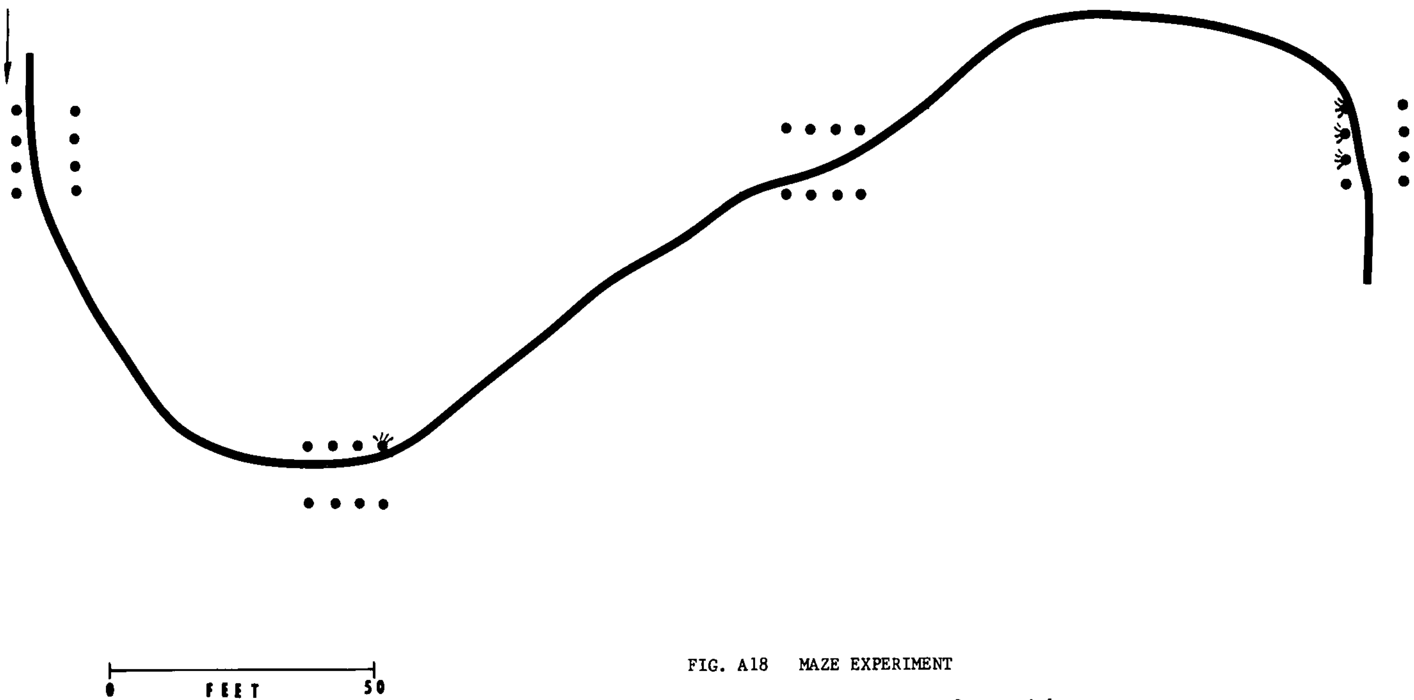


FIG. A18 MAZE EXPERIMENT

7.1 fps 0 sec. delay
DRIVER B WITHOUT PREDICTOR

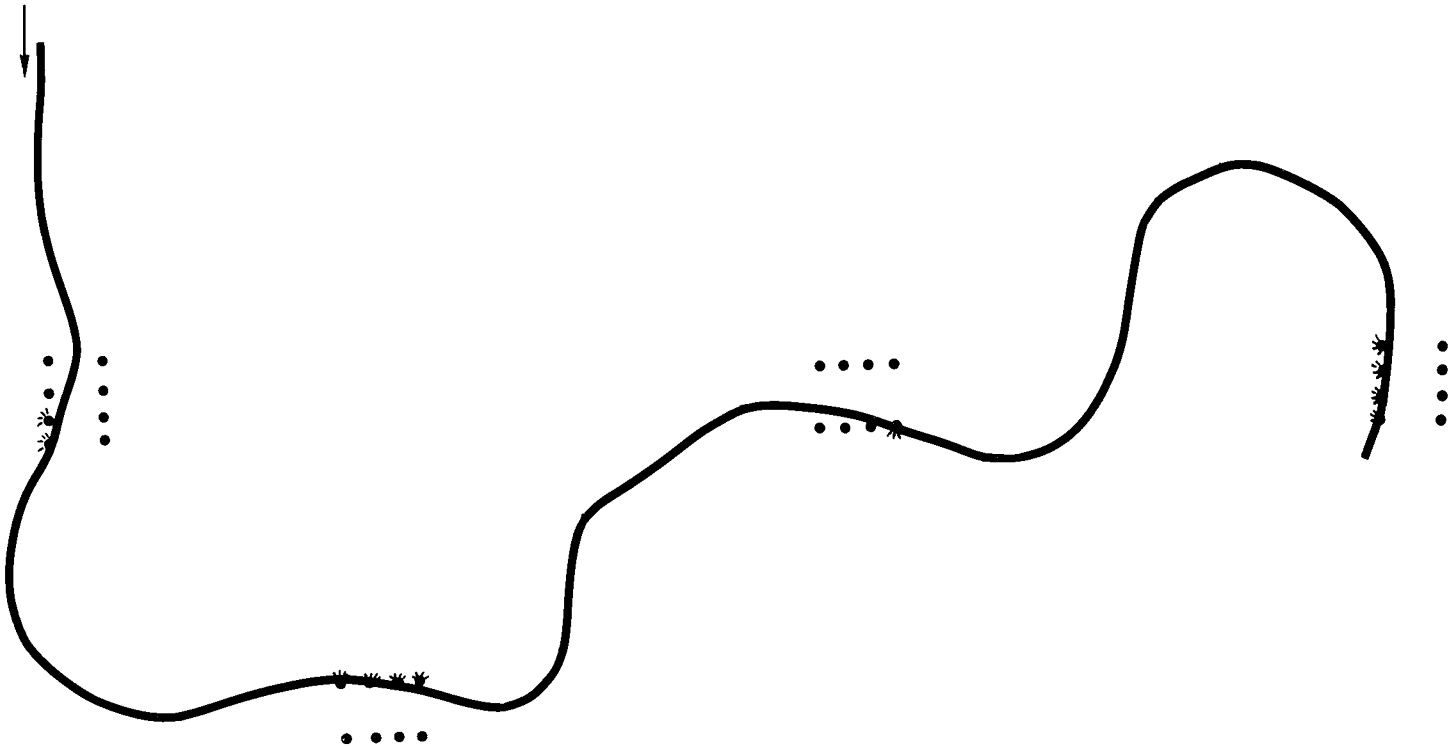


FIG. A19 MAZE EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER B WITHOUT PREDICTOR

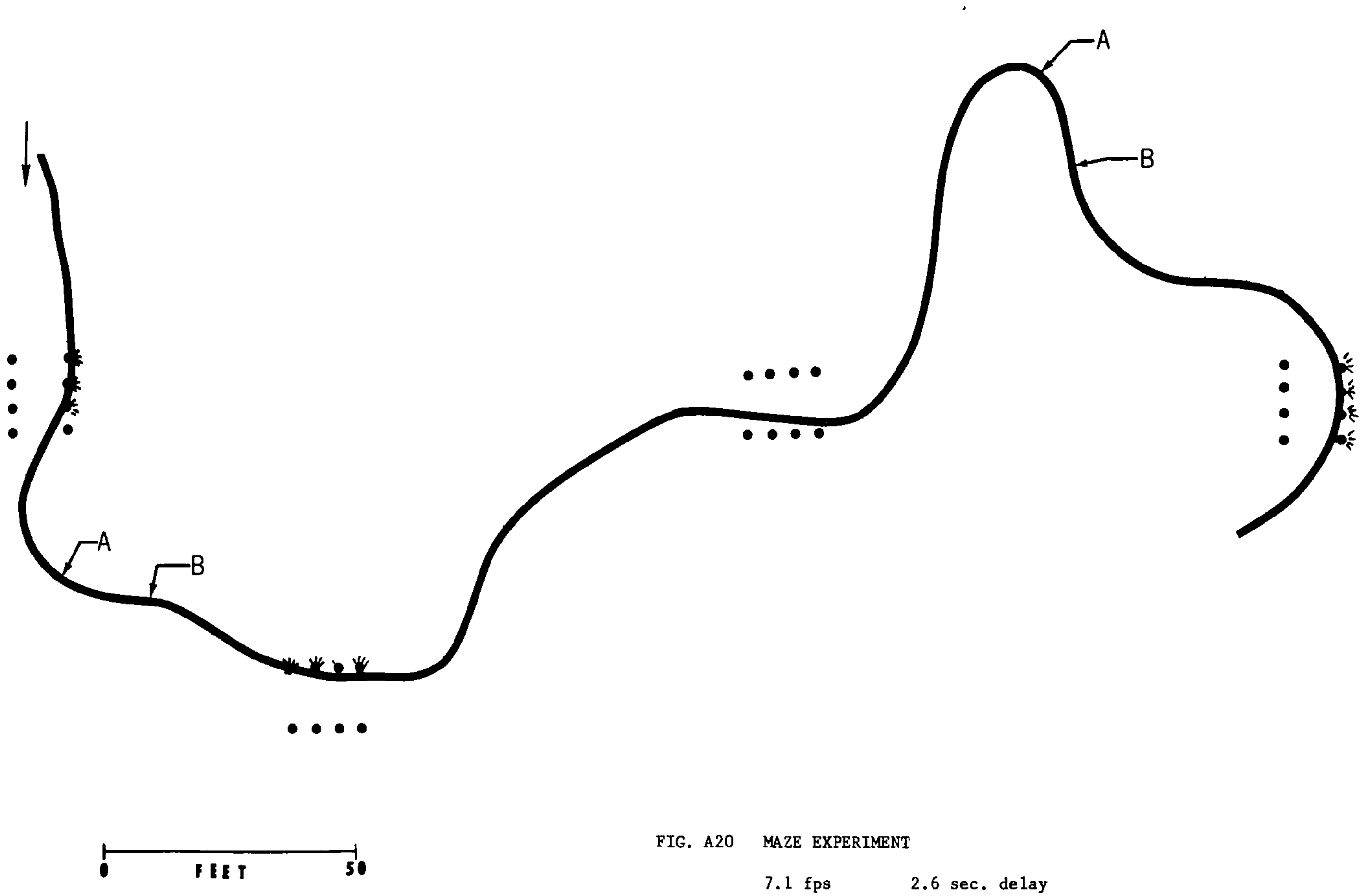


FIG. A20 MAZE EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER B WITH PREDICTOR

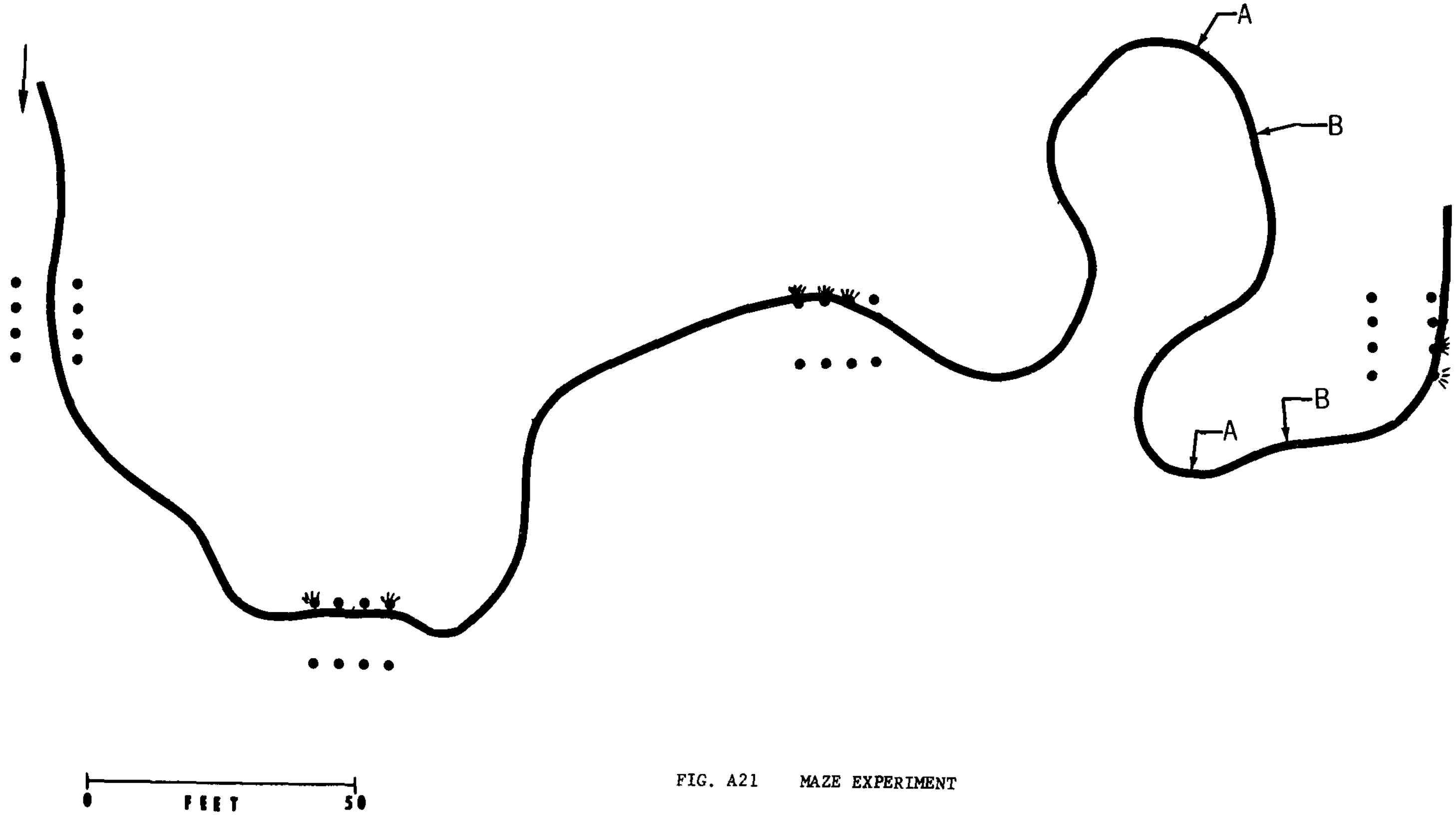


FIG. A21 MAZE EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER B WITH PREDICTOR

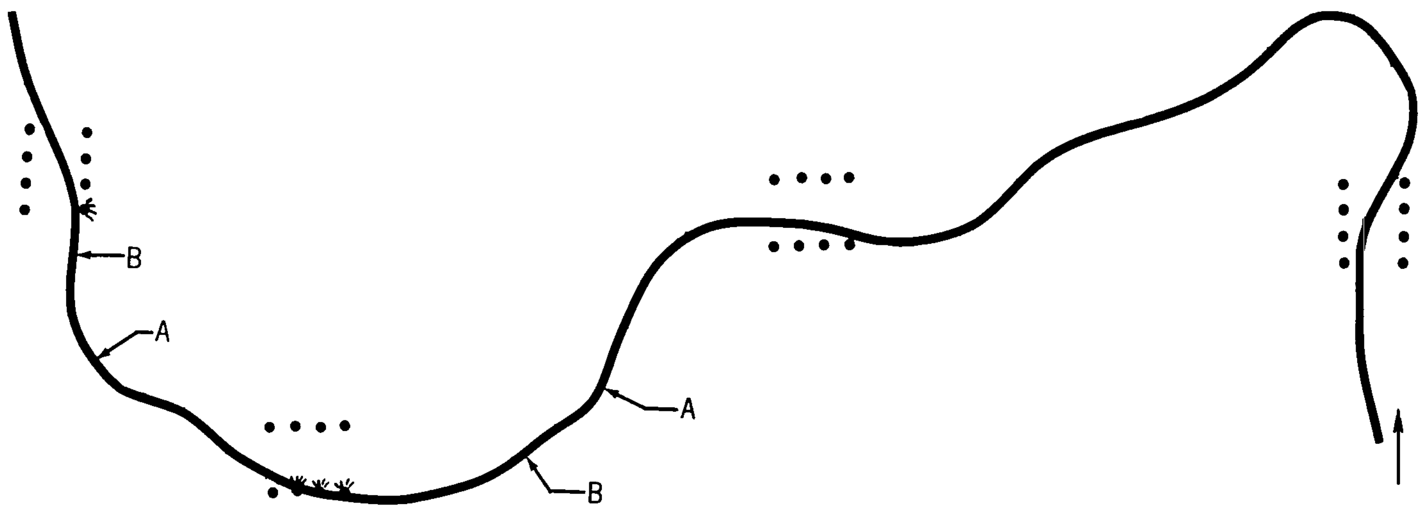


FIG. A22 MAZE EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER B WITH PREDICTOR

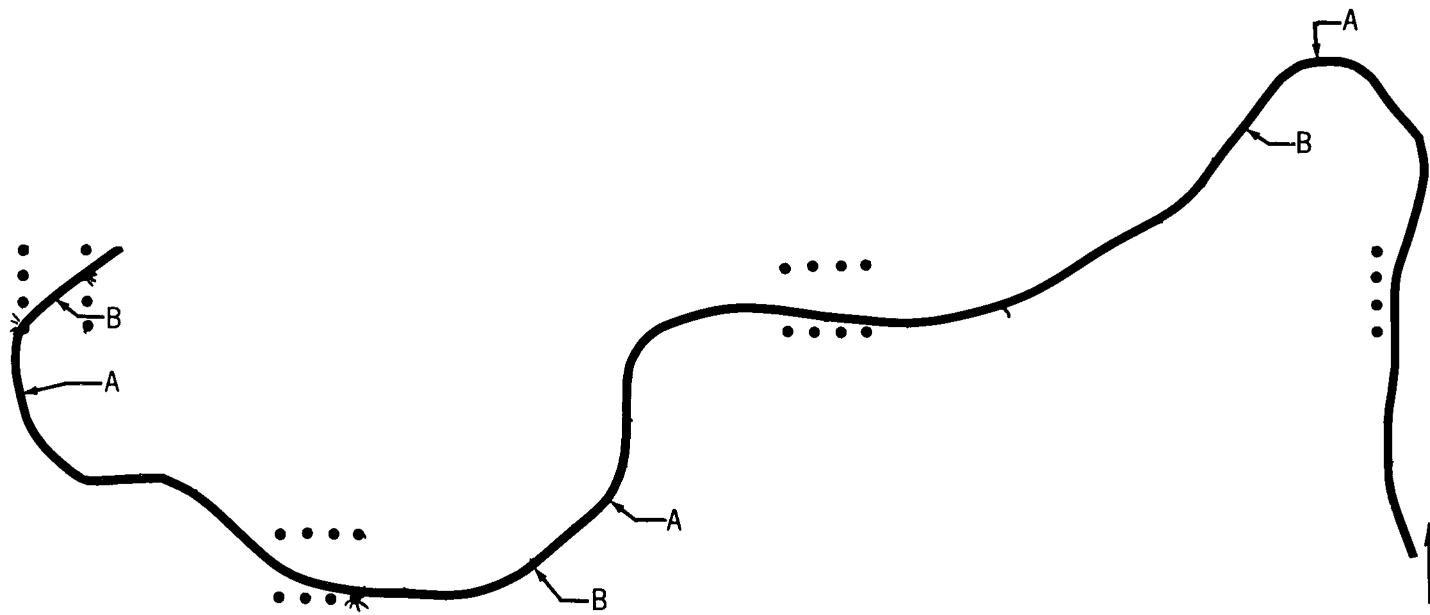


FIG. A23 MAZE EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER B WITH PREDICTOR

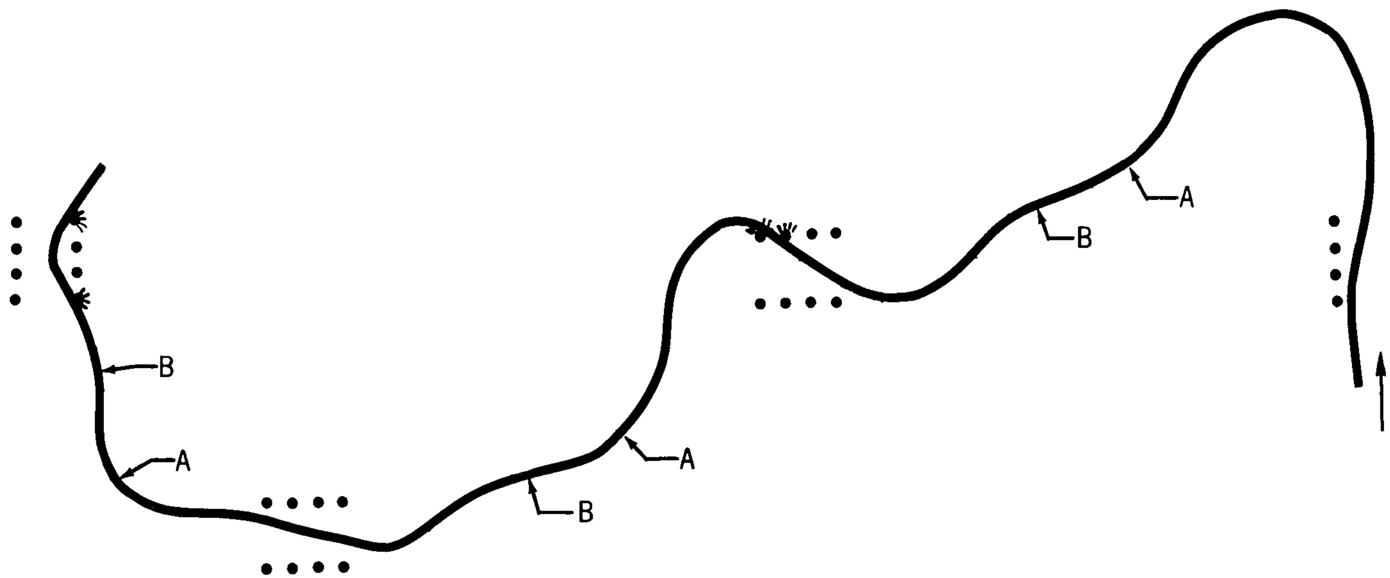


FIG. A24 MAZE EXPERIMENT

7.1 fps 2.6 sec. delay
DRIVER B WITH PREDICTOR

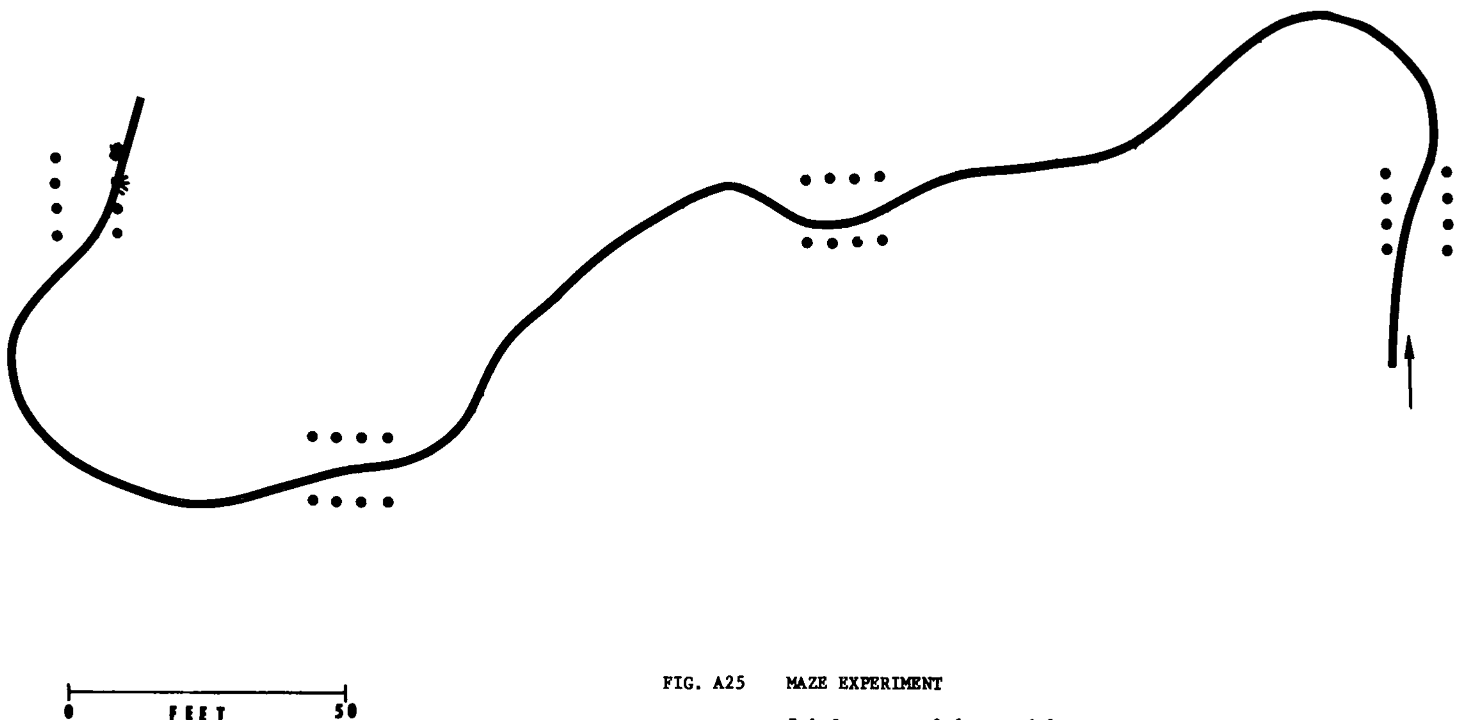
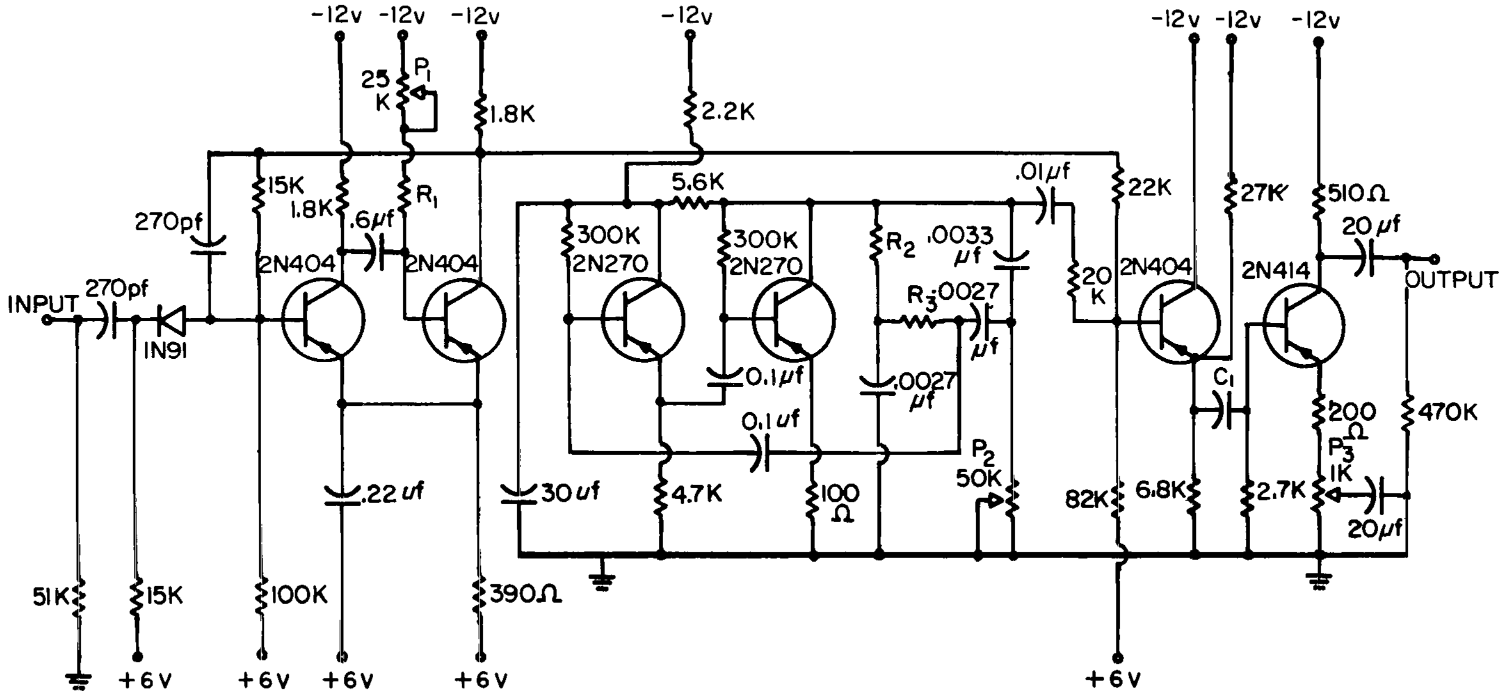


FIG. A25 **MAZE EXPERIMENT**

7.1 fps 2.6 sec. delay
DRIVER B WITH PREDICTOR

APPENDIX B

CONTROL SYSTEM SCHEMATICS



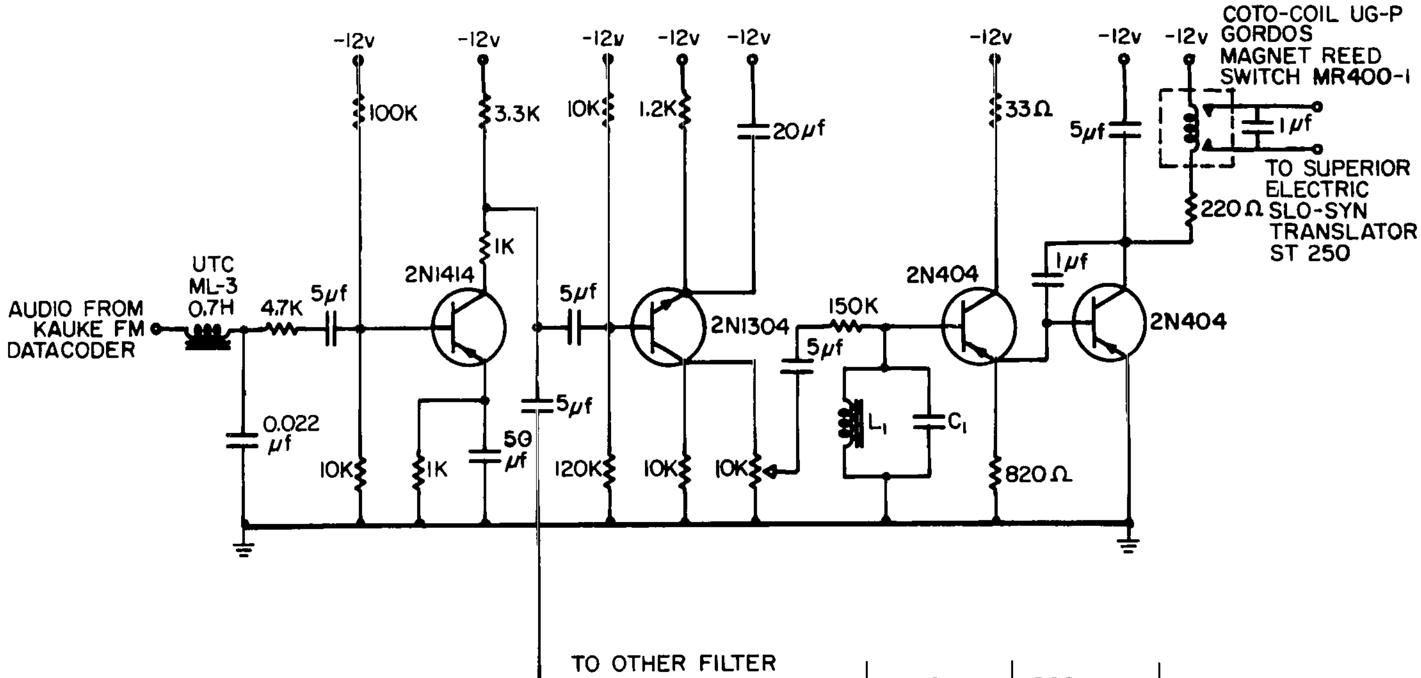
	RIGHT PULSES 1390 cps	LEFT PULSES 960 cps
R_1	39K	50K
R_2	100K	150K
R_3	100K	150K
C_1	.022 µf	.033 µf

P_1 PULSE LENGTH ADJUSTMENT

P_2 OSCILLATOR FREQUENCY ADJUSTMENT

P_3 OUTPUT GAIN ADJUSTMENT

FIG. B1 TONE GENERATING CIRCUIT



	1390 cps	960 cps
L_1	UTC ML-2 0.4 H	UTC ML-3 0.7 H
C_1	0.032 μf	0.04 μf

FIG. B2 CONTROL STATION PULSE FILTER

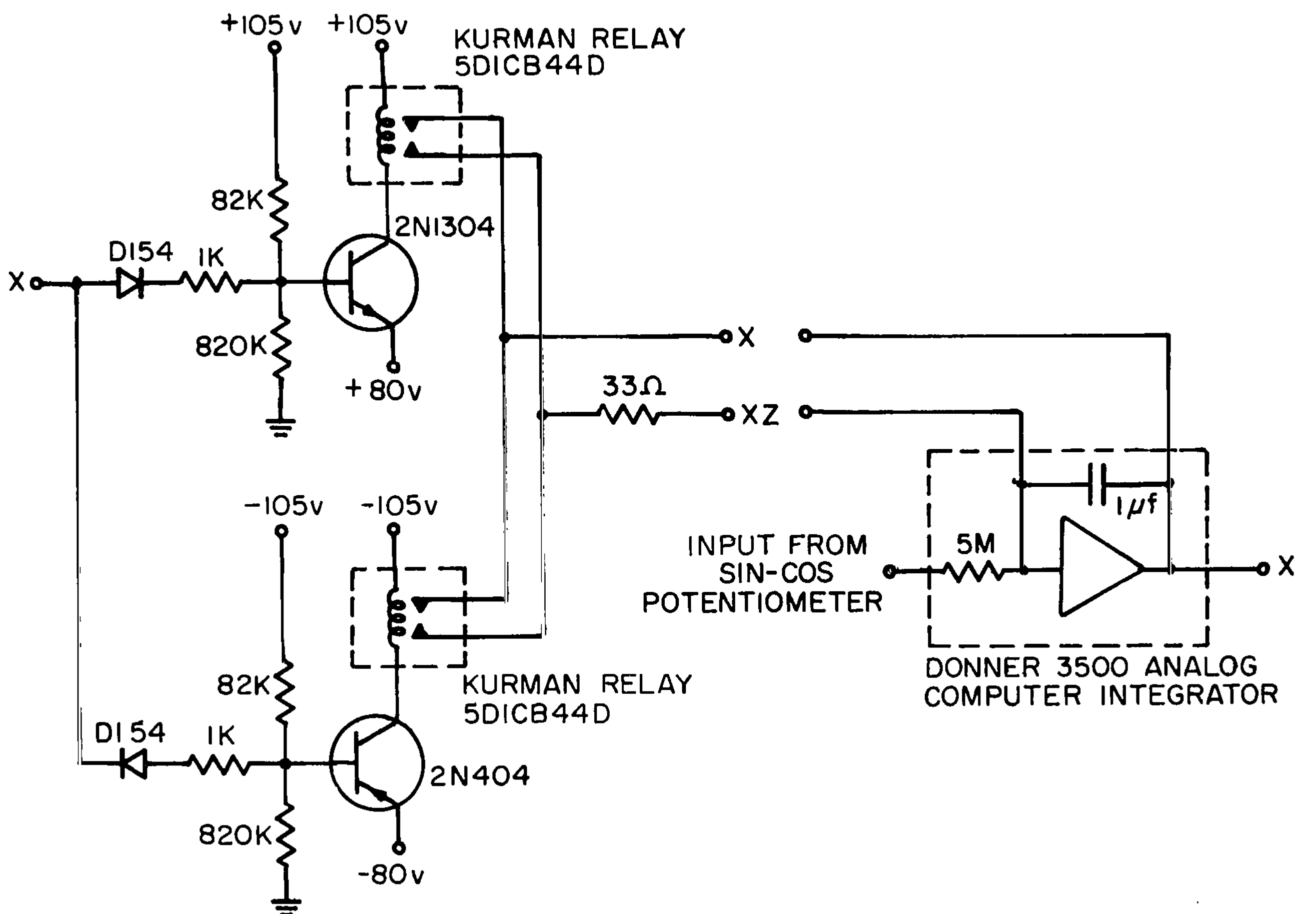


FIG. B3 COMPUTER RESET SWITCH

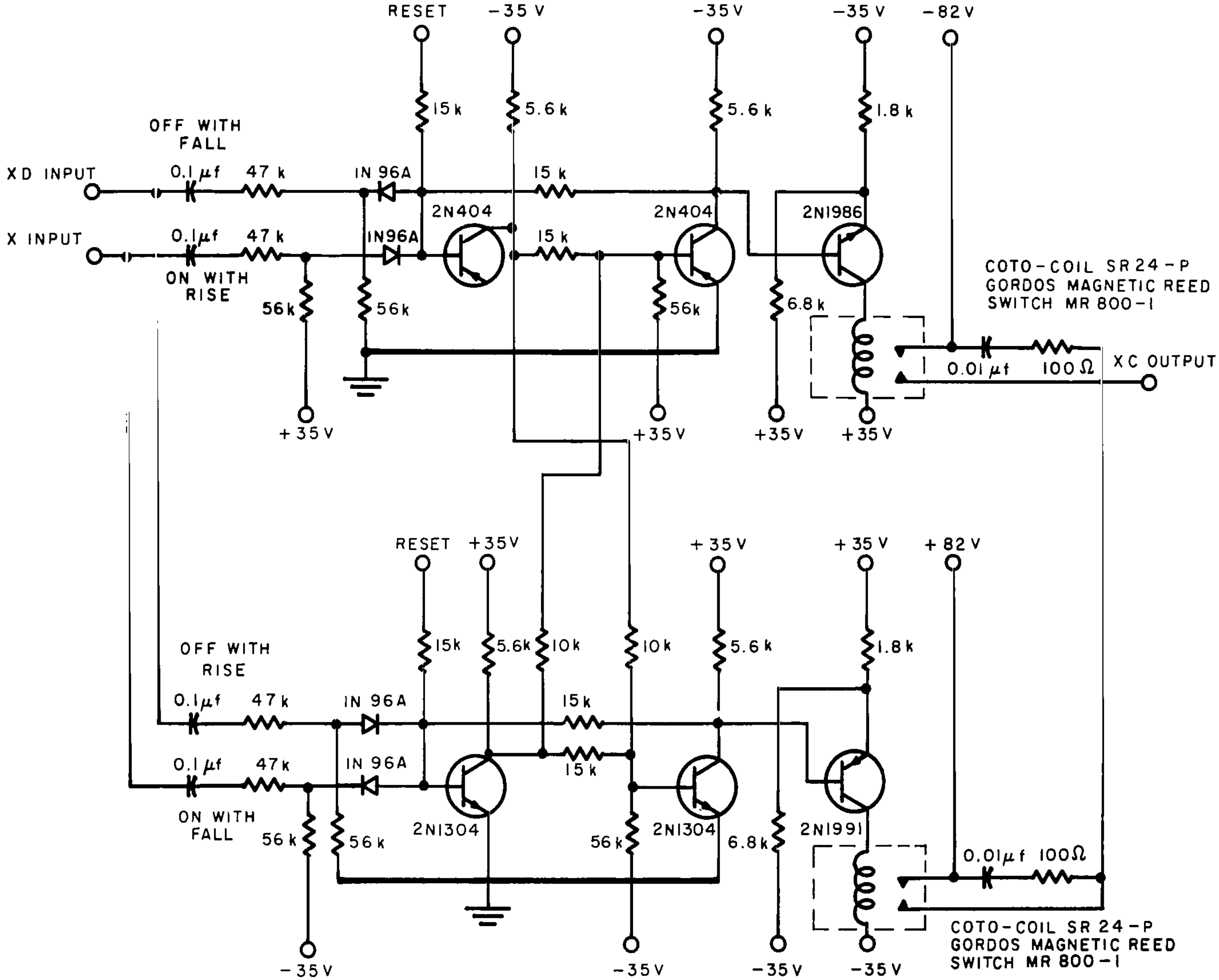
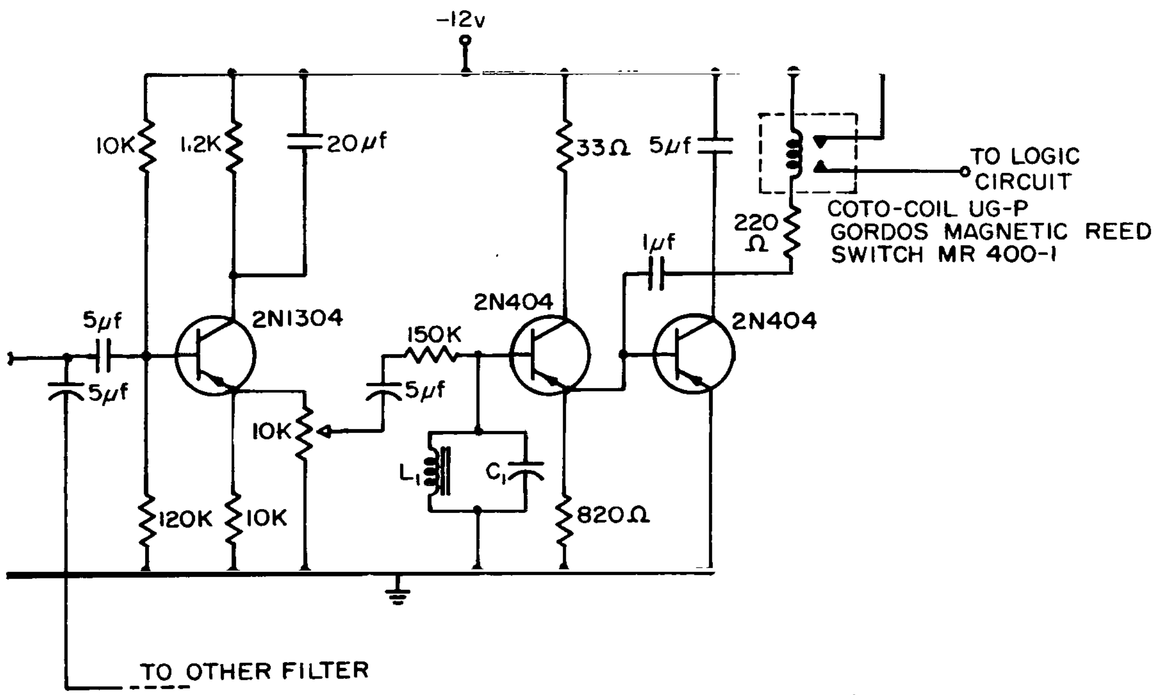


FIG. B4 COMPUTER RESET CORRECTION SWITCH



	1390 cps	960 cps
L_1	UTC ML-3 0.7 H	UTC ML-3 0.7 H
C_1	0.018μf	0.04μf

FIG. B5 VEHICLE STEERING FILTER

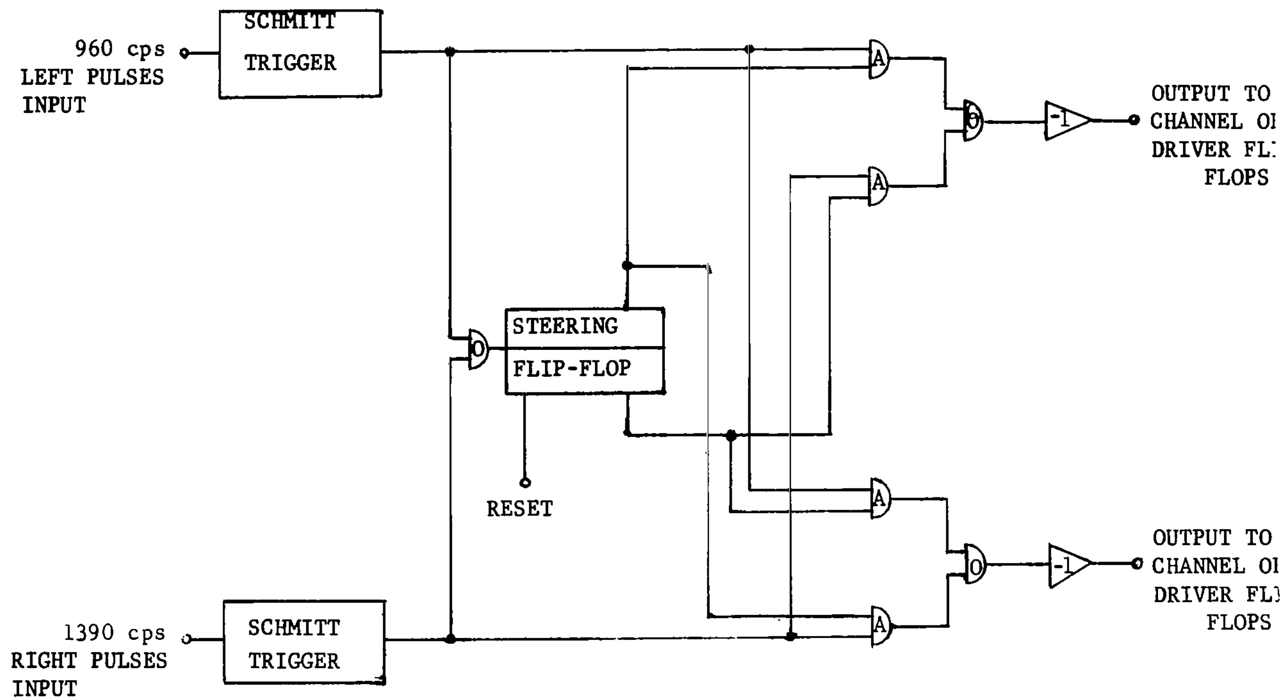


FIG. B6 VEHICLE STEERING LOGIC CIRCUIT BLOCK DIAGRAM

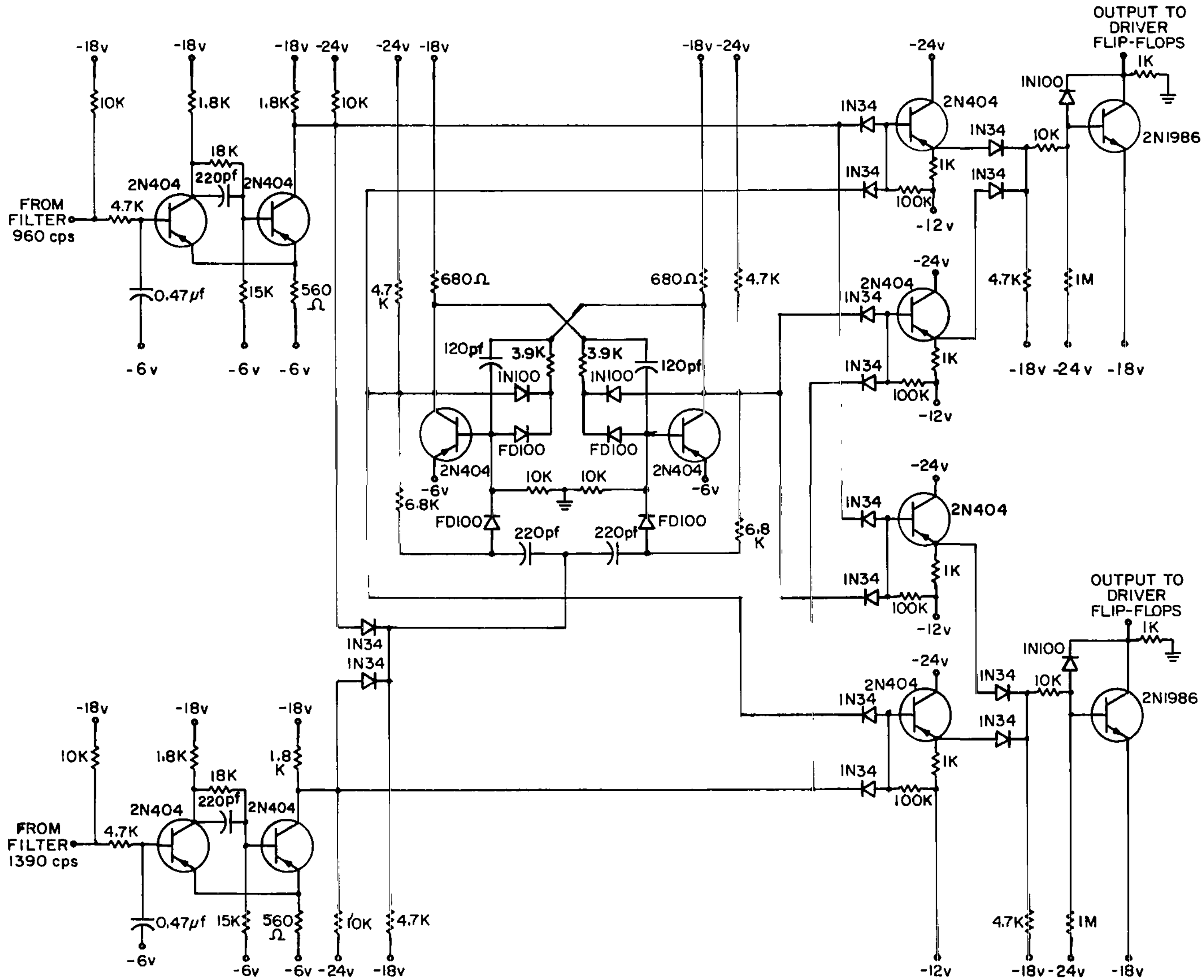
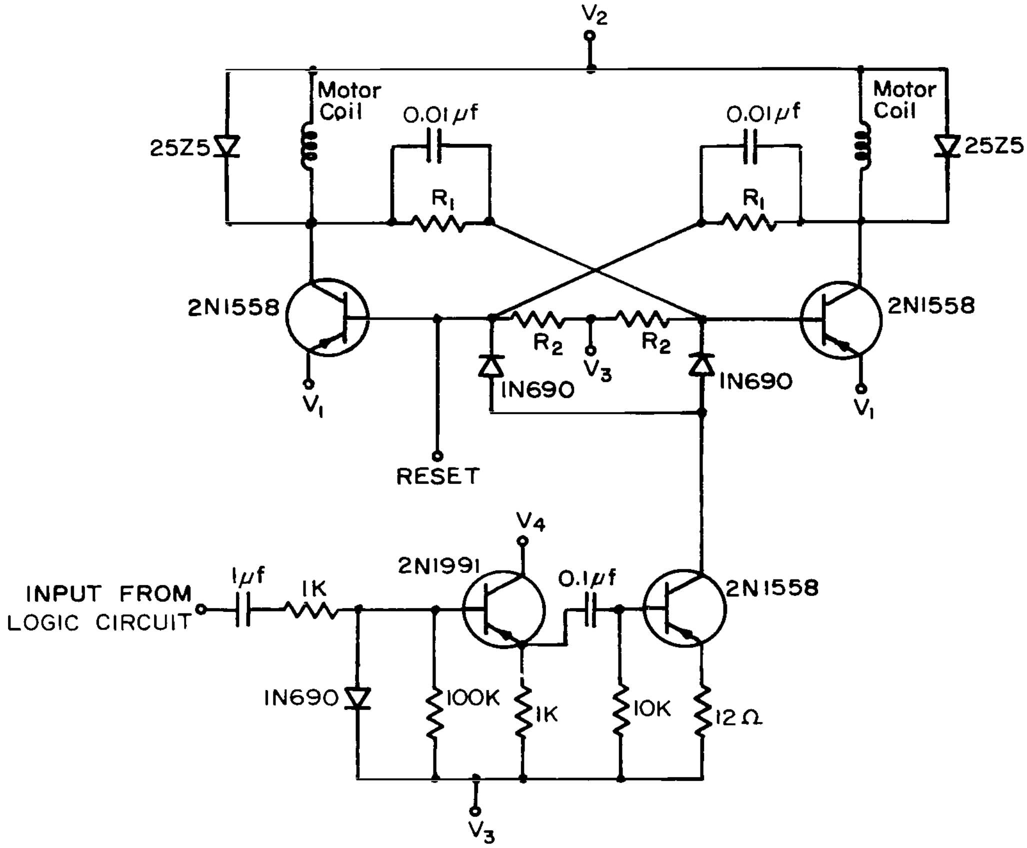


FIG. B7 VEHICLE STEERING LOGIC CIRCUIT SCHEMATIC



SUPERIOR ELECTRIC STEPPING MOTOR	COIL VOLTAGE	R_1	R_2	V_1	V_2	V_3	V_4
X 1000	0, -12 v	100 Ω	220 Ω	0v	-12v	+4.5v	-12v
X 1000	-12 v, -24 v	"	"	-12v	-24v	-7.5v	-24v
SS 400	0, -24v	220 Ω	470 Ω	0v	"	+4.5v	-12v

FIG. B8 VEHICLE STEERING DRIVER FLIP-FLOP SCHEMATIC

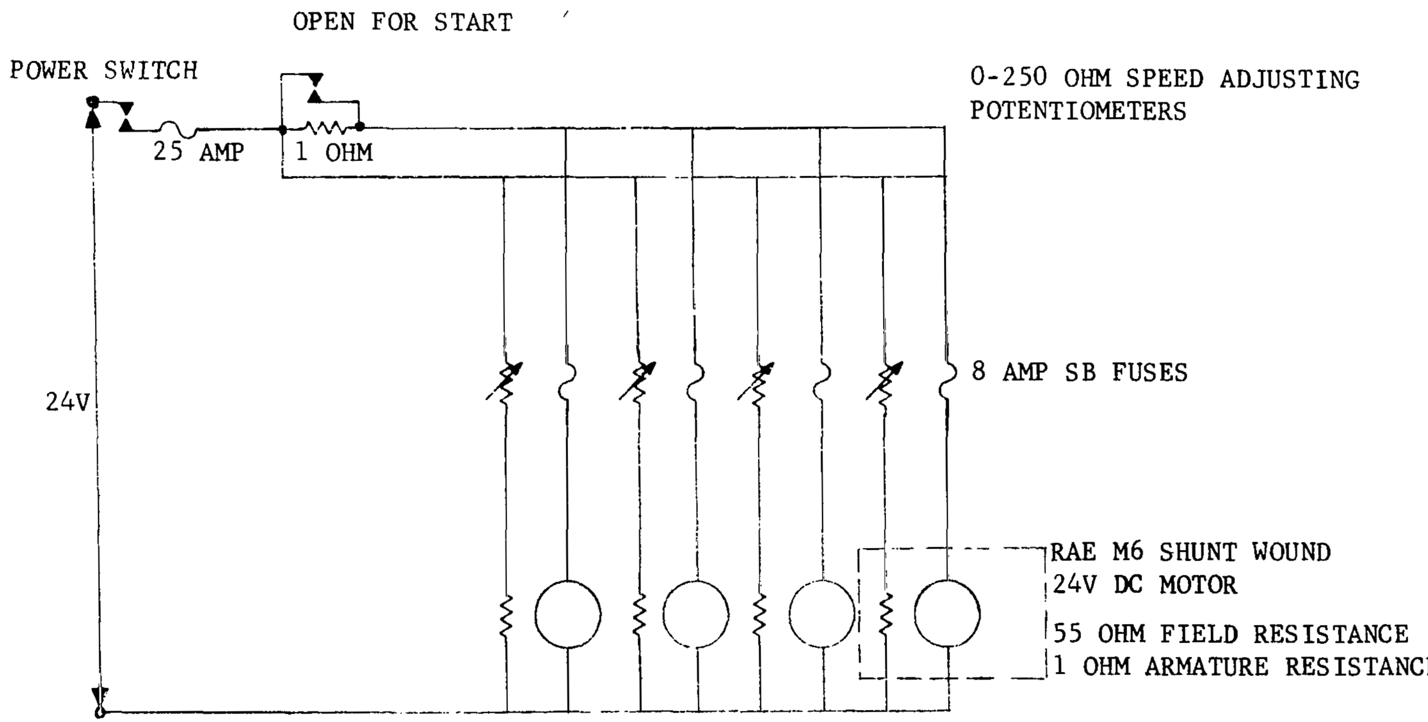


FIG.B9 VEHICLE DRIVE MOTORS